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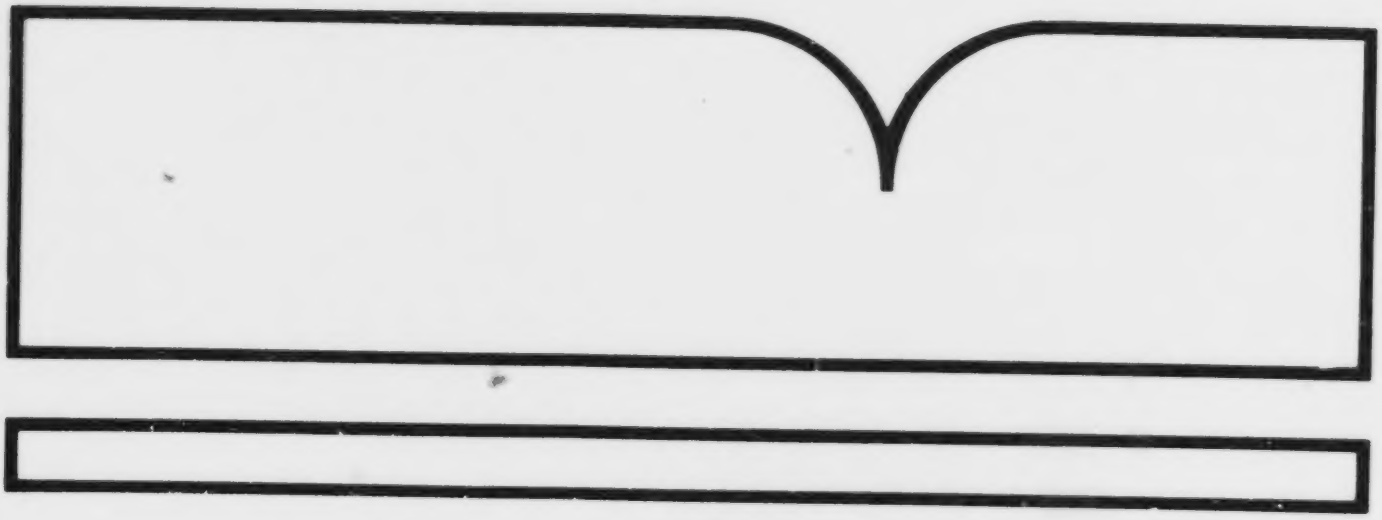
Guidelines for the Reduction of Emissions and Efficiency Improvement for Refinery Process Heaters

KVB, Inc., Irvine, CA

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

May 83



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GUIDELINES FOR THE REDUCTION OF EMISSIONS AND EFFICIENCY IMPROVEMENT FOR REFINERY PROCESS HEATERS

by

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This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

ABSTRACT

This manual contains guidelines for the operation, adjustment, and modification of refinery process heaters to achieve reduced emissions and increased efficiency. Combustion fundamentals are summarized and test data obtained on this contract from previous subscale and full-scale process heaters are reviewed. All of the results cited pertain to natural draft, vertically fired heaters; however, many of the combustion modification techniques discussed in this manual are expected to be applicable to forced draft heaters and horizontally fired heaters as well. Recommended procedures for carrying out combustion adjustments on process heaters are given. The most promising combustion modification to reduce refinery heater emissions and improve efficiency - staged combustion air lances - is discussed in detail. Information appropriate to the design, operation, and maintenance of a staged combustion air lance system for a process heater is presented. Cost effectiveness estimates for such a system are also given. It is expected that through the proper use of a staged combustion air system and the heater adjustment procedures described in this manual, the fuel costs for a typical refinery heater will be reduced by approximately 4 to 5 percent and the NO_x emissions may be reduced to 1/2 to 1/3 of baseline levels.

LIMITATIONS ON APPLICATION OF GUIDELINES

The contents of this manual are offered as guidance. The United States Government, its employees, and KVB, Inc. do not assume responsibility or liability for consequences arising from the implementation or failure to implement the guidance contained herein. The contents of this manual should not be construed as an endorsement by the Environmental Protection Agency of any product or manufacturer.

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Parts of this manual have been prepared from several sources of information within KVB, Inc.

SECTION 1.0

INTRODUCTION

1.1 SUMMARY AND OBJECTIVES

This guideline manual is intended to assist manufacturers and operators of natural draft process heaters in the petroleum refining industry in achieving maximum efficiency with minimum pollutant emission. The means for achieving such optimized heater performance have been investigated over a period of several years through an exhaustive field test program encompassing both subscale and pilot-scale heater tests. These methods include operating variable optimization (e.g., amount of excess air and air distribution and mixing patterns) applied either alone or in combination with hardware modifications such as staged combustion air lances, altered fuel injection geometry, low-NO_x burners, flue gas recirculation, and steam injection. Section 2.0 reviews the modifications studied and the results obtained from the field test program.

This manual will focus on the use of operating variable changes (Section 3.0, Combustion Adjustments to Process Heaters) and the implementation of the most promising of the hardware modifications investigated for process heaters - staged combustion air lances (Section 4.0). Combustion adjustments and the staged combustion modification have been successfully applied in combination to a natural draft process heater for a period of 30 days. Their application resulted in significant increases in the thermal efficiency of the heater while at the same time reducing NO_x emissions by 60 percent or more.

Methods for conducting emission measurements, optimizing excess air level, and establishing the proper burner register settings are discussed in Section 3.0. Also covered in that section are suggested procedures for monitoring heater performance once the unit has been properly adjusted. This section should be of particular interest to heater operators.

Section 4.0 covers the design, operation, and maintenance of a staged combustion air system which uses stainless steel pipes (or "lances") to introduce combustion air downstream of the burner injection plane. The costs and cost effectiveness of this system are included as Appendix A. The first part of Section 4.0 covering the design of the staged air system is aimed primarily at heater manufactuers while the remaining parts should be of interest to both manufacturers and operators.

Conversion factors commonly used in dealing with emission measurements are tabulated in Appendix B while the formulae used to correct emission measurements for moisture and excess air are given in Appendix C.

This manual provides guidelines for combustion modifications which apply to new or existing natural draft heaters. The test results described here are given for a vertical cylindrical firebox configuration, however, the combustion modifications are expected to be applicable to vertical rectangular and horizontally fired heaters as well.

Although the experimental work discussed in Section 2.0 was conducted on a crude oil heater, the modifications and adjustments discussed in Sections 3.0 and 4.0 are expected to be applicable to other heater types (e.g., cracking heaters or reformer heaters) since the process tube wall temperature distribution does not appear to be significantly altered by these changes in heater operation. In addition, the use of burner adjustments and staged combustion air is not limited, in principle, to natural draft heaters only. Mechanically drafted units both with and without combustion air preheat are expected to lend themselves well to such modifications based on previous experience with industrial and utility boilers. In a particular example, staged air lances applied to a mechanically drafted industrial boiler resulted in a NO_x emission reduction of 42 percent (while increasing the unit's thermal efficiency by one-half to one percent). (Ref. 1)

The remainder of this section covers the basic principles of combustion which are especially important in understanding heater performance with respect to efficiency and emissions.

1.2 COMBUSTION FUNDAMENTALS*

The heat energy in all fossil fuels (coals, fuel oils, and natural gases) is released during the combustion process as the carbon and hydrogen in the fuel react with oxygen to produce a high temperature flame. The burning of carbon and hydrogen with oxygen would ideally produce an exhaust gas consisting of carbon dioxide (CO_2) and water vapor (H_2O) which are considered harmless combustion by-products. Unfortunately, real combustion systems differ from this ideal situation due to the more complex make-up of the fuel itself plus the non-ideal characteristics of the actual burning process. As a result, the exhaust products from process heaters contain additional gaseous and solid materials, some of which are identified as serious environmental pollutants. Some are products of incomplete combustion and are important from an efficiency standpoint, since they represent a waste of available heat that is lost from the heater stack.

Air is the convenient and nonvarying source of oxygen for nearly all industrial combustion processes. The composition of air is roughly 21 percent oxygen (O_2) and 78 percent nitrogen (N_2) by volume with traces of other gases including argon and carbon dioxide. Under perfect combustion conditions, there is a so-called "theoretical amount" of air which will completely burn a given amount of fuel with no excess air remaining. In practice, however, more air than the theoretical amount must be supplied to the burner to ensure complete burning of the fuel. The actual quantity of excess air required at a particular heater depends on many factors such as fuel type and composition, furnace design, heater firing rate, and the design and adjustment of the burners. If enough air is not provided, unburned fuel, smoke and other products of incomplete combustion such as carbon monoxide (CO) and soot are emitted from the stack, resulting in pollution, wasted fuel energy, and a potential for explosion. If too much excess air is supplied to the burner, the heater efficiency will be reduced because some fuel is used simply to heat

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*This section is adapted from EPA Report No. 600/8-77-003a, Guidelines for Industrial Boiler Performance Improvement.

the unneeded air which is exhausted out the stack. The amount of excess air can also influence the formation and emission of nitrogen oxides (NO_x) as discussed in a later section.

1.2.1 Furnace Excess Air

Excess air is a primary heater operating variable and an important factor in the following discussions. It is therefore appropriate to include a brief discussion of this term and the methods available for determining the quantity of excess air at the heater.

Accurate fuel and air flow measurements would provide a direct determination of the heater air/fuel ratio and excess air, but these measurements are frequently not available at process heater installations. An alternate means for determining heater excess air utilizes measurements of specific gases in the stack and the known relationships between their concentration and percent excess air for a particular fuel.

Excess air in the heater is evident from the presence of oxygen in the flue gas. This oxygen content is customarily referred to as excess air, flue gas O_2 or stack O_2. However, the terms "excess air" and "stack O_2" should not be confused to mean the same thing. As the excess air is increased at the heater, one would expect that the oxygen concentration in the stack gases would also increase, and, indeed, this is the case. Figure 1-1 shows this relationship between stack O_2 and excess air for typical natural gas, oil and high grade coal fuels. (The oxygen concentration in the stack gas will hereafter be referred to as "stack O_2.")

Some heater operators are accustomed to judging heater firing conditions based on stack CO_2 measurements (as opposed to using stack O_2) and the CO_2 versus excess air dependence is also shown in Figure 1-1. While both approaches are equally valid for determining heater excess air, the use of stack O_2 is preferred for the following reasons:

1. The relation between O_2 and excess air is not highly affected by fuel composition. This is evident in Figure 1-1 where the O_2 versus excess air curves for natural gas, oil and coal fuels are nearly coincident. On the other hand, CO_2 versus excess air curves exhibit a wide variation with fuel type.

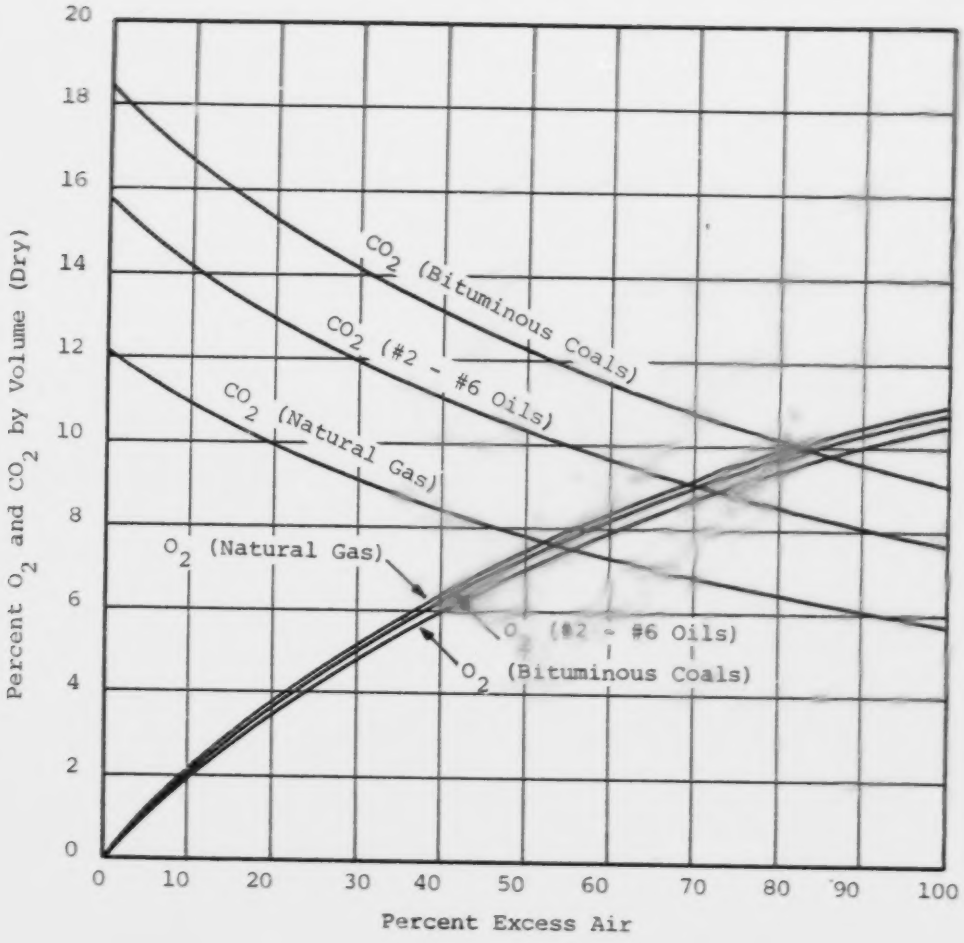

Figure 1-1. Relationship between heater excess air and stack gas concentrations of oxygen (O_2) and carbon dioxide (CO_2) for typical fuel compositions.

2. Measurement of CO_2 requires a much greater precision than O_2 measurements to obtain the same accuracy in excess air. This is especially true when firing with low excess air which is generally the preferred condition for high heater efficiencies. For example, suppose it is desired to establish the excess air to within ± 2 percent. If the heater is operating in the region of 20 percent excess air on oil fuel, the CO_2 would have to be measured to within ± 1.5 percent accuracy (13.0 ± 0.2 percent CO_2), while an O_2 measurement accuracy of only ± 8 percent (3.7 ± 0.3 percent O_2 would be required.

3. CO_2 is a product of combustion whereas stack O_2 is more immediately associated with excess air conditions in the heater. The O_2 measured in the stack gases is the actual surplus of oxygen in the furnace available for the combustion process. As lower and lower excess air is present in the furnace, the stack O_2 approaches zero (regardless of fuel type) while the CO_2 increases, approaching some constant value which is dependent upon the fuel composition.

4. Instrumentation for O_2 measurements is generally less expensive and more reliable as a class than CO_2 instrumentation. Many continuous CO_2 instruments are infrared spectrometers which are expensive and not very portable when compared to the polarographic (fuel cell) type continuous O_2 analyzers.

In following sections of this manual, stack O_2 will be used exclusively as an indicator for excess air. It is strongly recommended that the use of stack O_2 be adopted by all heater operators. However, for those who still prefer to think in terms of CO_2, it is possible to convert O_2 to CO_2 using curves such as those in Figure 1-1 for the particular fuel being fired.

One final note concerns the interpretation of heater excess air as it relates to excess air at the burner. For heaters with a single burner, the percent excess air at the burner is said to be the same as the heater excess air (percent excess air at the stack). For multi-burner heaters, the situation can be complicated if the fuel and air are not equally distributed to all the burners. With equal fuel and air distribution, the fuel/air ratio and percent excess air at all burners is the same and equal to the percent excess air at the heater. However, when the fuel and/or air varies from burner to burner (due to dissimilar air register settings, eroded fuel injection

orifices, etc.), the fuel/air ratio and burner excess air will also vary. The use of staged air or other air injection ports away from the burner region will of course result in less excess air at the burner than indicated by the stack O_2.

One must also be aware that air leaks in the furnace upstream of the O_2 sampling location or leaks in the extractive sampling system may cause the stack O_2 measurement to be higher than the O_2 concentration at the heater. For this reason, one must pay particular attention to maintaining the sample system integrity and minimizing air leaks into the heater (or measuring the amount of such leaks by taking an O_2 measurement in the firebox itself).

1.2.2 Nitrogen Oxides

Combustion temperatures on the order of 2200 K (3500°F) are reached in the flame zone of process heaters. When oxygen and nitrogen are both present at such high temperatures, a fraction of these will combine to form NO_x. Nitrogen oxides formed in this manner are difficult to prevent altogether, since all three ingredients (oxygen, nitrogen and high temperature) are integral parts of the combustion process. Nitrogen is the major constituent in the combustion air and its elimination would be very impractical. Most of the NO_x reduction techniques described in the following sections are generally viewed to be effective as a result of lower peak flame temperature, reduced availability of oxygen in the flame or a combination of both. Oxygen and temperature are important flame parameters affecting stability, radiant heat release, combustible burnout, flame appearance and other factors related to heater operation. Therefore, the successful application of NO_x reduction techniques involve more than just reducing NO_x emission levels.

Equal consideration must be given to these other factors to assure safe, reliable and efficient operation. This aspect of implementing low NO_x firing will involve a certain amount of subjective interpretation of flame conditions in the furnace coupled with an evaluation of heater efficiency, feed conditions and other operational factors.

Nitrogen oxides produced by the combining of atmospheric nitrogen and oxygen under the influence of high flame temperatures is generally referred to

as "thermal NO_x." Conventional solid and liquid fuels (even some natural gas fuels) contain quantities of nitrogen-bearing compounds. A fraction of this nitrogen also combines with oxygen in the flame to produce what is called "fuel nitrogen NO_x" or simply "fuel NO_x." This "fuel NO_x" plus the "thermal NO_x" make up the total NO_x emitted from the stack. In some cases with a high nitrogen content fuel, the "fuel NO_x" can contribute more than half of the total NO_x emissions.

The formation of "fuel NO_x" is not presently well understood. There is some evidence that "fuel NO_x" can be reduced by lowering the available oxygen in the flame. Switching to a fuel which contains less nitrogen has also produced lower total NO_x; however, this is not always predictable for fuel variations within the same fuel type (i.e., No. 6 oils, No. 2 oils, etc.). It should also be mentioned that measurements of total NO_x at the stack or furnace outlet will not distinguish between "thermal NO_x" and "fuel NO_x." NO_x variations measured under various heater operating modes may result from combined effects on both NO_x components.

Finally, while oxygen availability and flame temperature appear to be the major combustion parameters affecting NO_x formation, the absolute levels of NO_x emitted from the stack will also depend on a variety of other factors. Different types of fuels generally exhibit a different range of NO_x emissions. This is due to differences in fuel nitrogen already mentioned plus fundamental differences in the fuel burning characteristics, general requirements of the associated burning equipment, and so on. For a particular fuel composition, variations in NO_x emissions from one heater to another also suggest the importance of burner and furnace design and the specific flow patterns of the flame within the furnace. At any given heater with a constant fuel, the NO_x emissions are also slightly dependent on firing rate.

1.2.3 Heater Efficiency

The term "heater efficiency" as used in this manual pertains to the degree to which the heater extracts the total available heat energy from the fuel. Some loss of heat from the unit is unavoidable and as a consequence, heater efficiency is always less than 100 percent. However, some of these

efficiency losses can be minimized or eliminated by proper operating and maintenance practices discussed in Section 3.

Heater efficiency losses arise from four major sources.

1. Heat carried away (out the stack) by the hot flue gases. This loss is usually called "dry flue gas" loss. Hotter stack temperature and larger quantities of excess air increase this loss.

2. Latent heat of water vapor present in the flue gas. (Water vapor results from the combustion of hydrogen contained in the fuel and from moisture present in the fuel and combustion air.) This loss arises from the fact that water vapor contains more heat energy than an equal weight of liquid water. The latent heat would be recovered only if the water vapor were allowed to condense out before the flue gases leave the heater. Since this may be impractical in conventional heaters, (due to corrosion problems and reduced plume rise), the latent heat has not been considered recoverable. This situation may be changing with the advent of modern waste heat recovery devices.

3. Unburned fuel and products of incomplete combustion. These include all solid and gaseous combustible material carried away in the flue gases. This loss is usually referred to as "combustible loss" or "unburned fuel loss." Improperly adjusted burning equipment or an inadequate quantity of excess air can lead to rapid increases in combustible losses.

4. Heat lost through the walls of the heater. This is generally termed "radiation loss" and includes heat radiated to the surroundings and the heat picked up by the ambient air in contact with the heater surfaces. The quantity of heat lost in this manner is fairly constant at different firing rates and as a result, becomes an increasingly higher percentage of the total heat losses at the lower firing rates. Deteriorated insulation and furnace wall refractory will also increase these losses at all loads.

Figures 1-2 and 1-3 illustrate how the various efficiency losses are affected by changes in stack O_2 and firing rate. These results are based on actual measurements at a 4.6 MW_{th} boiler fired with natural gas but the general trends are also representative of many oil fired units. Of course, the actual values of the various efficiency losses will be different depending on specific fuel properties, heater/burner design, operating conditions, etc.

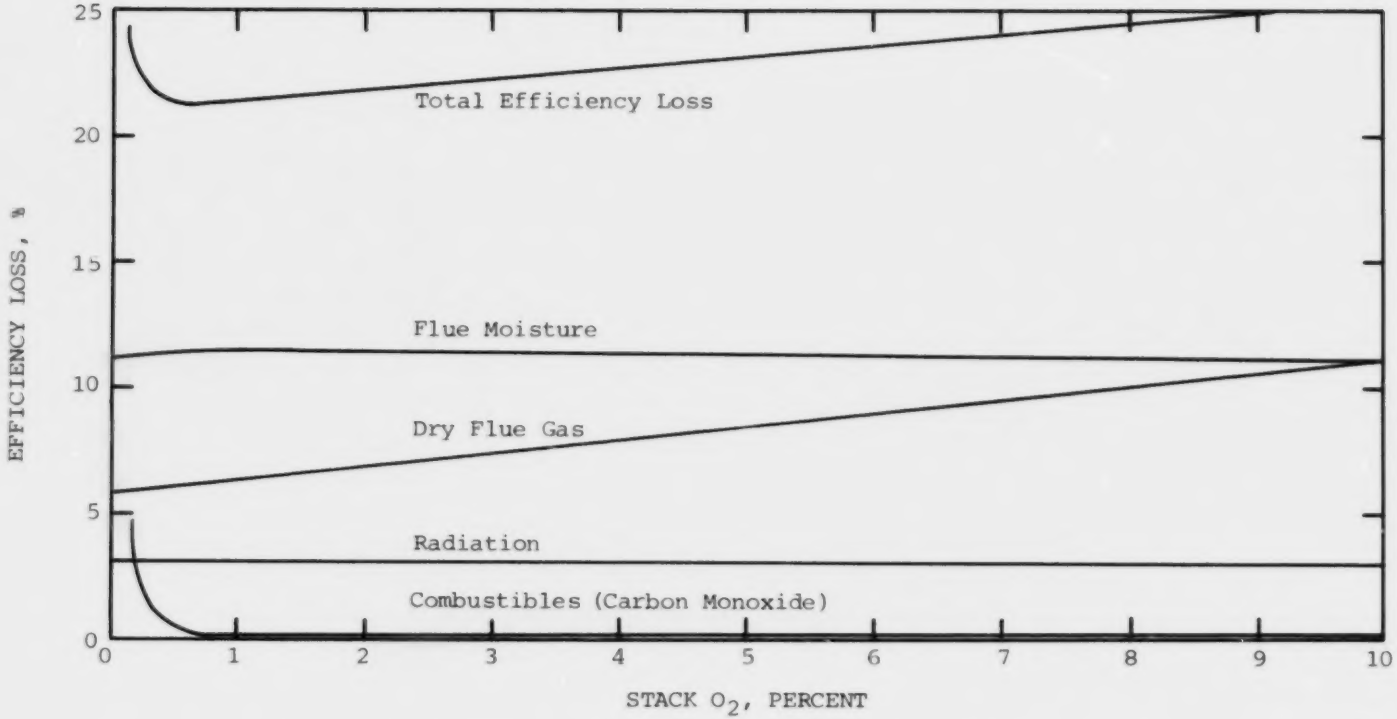

Figure 1-2. Variation in heater efficiency losses with changes in stack O_2.

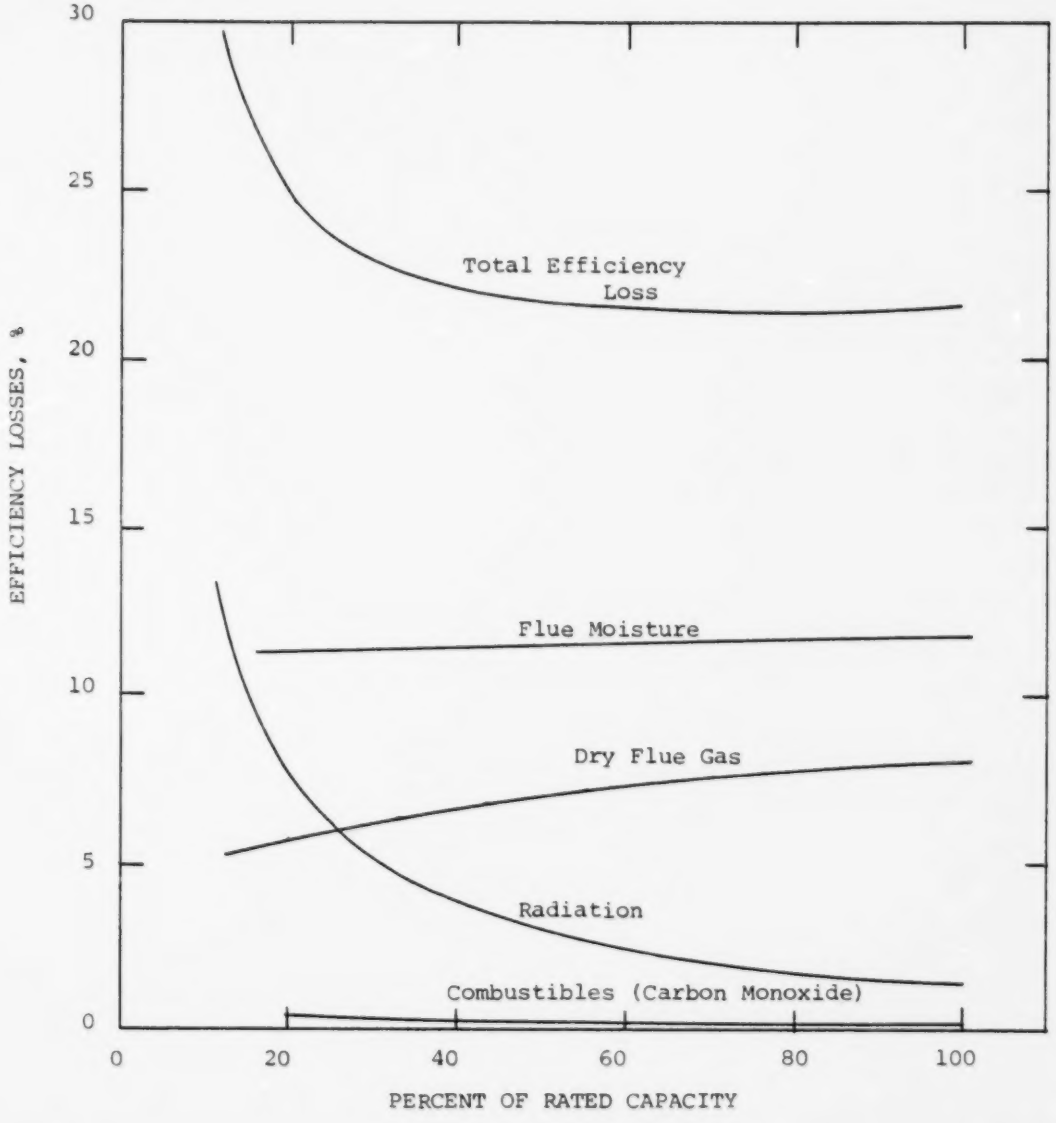

Figure 1-3. Variation in heater efficiency losses with changes in heater firing rate.

At each firing rate the highest heater efficiency is achieved by firing with the lowest practical O_2. For the particular example in Figure 1-2, the point of maximum efficiency occurred at about 0.5 percent O_2 where the total efficiency losses were at a minimum. (Stack O_2 levels at peak efficiency can vary significantly from heater to heater and with different fuels.) A further reduction in stack O_2 caused rapid increases in carbon monoxide and other combustibles which resulted in a very rapid deterioration in efficiency.

With high stack O_2, some fuel is used to heat unneeded excess air to the stack temperature where it is carried out the stack (resulting in higher "dry flue gas" losses and reduced efficiency). It might at first seem that large quantities of excess air would mix with the flame and cool it, resulting in a lower stack gas temperature. In practice, however, the reverse is true. High excess air does cool the flame and cool the furnace. But, at the same time, the heater must fire more fuel to generate the same quantity of energy and proportionately greater amounts of air are fed through the burner. Consequently, greater amounts of gas pass through the heater so quickly that they retain their heat instead of transferring it to the tubes. This explains why stack temperatures generally increase as the excess O_2 is raised, contributing to reduced efficiency.

It would be desirable to operate at the point of peak efficiency at each firing rate to minimize fuel wastage. However, as described later in this manual, there are certain limitations in typical heater combustion controls which require that heaters be operated at some point slightly below peak efficiency to avoid combustibles and potentially unsafe conditions.

Figure 1-3 illustrates that there are significant changes in efficiency losses as the firing rate is varied. Especially obvious are the "radiation loss" which increases at lower firing rates and the"dry flue gas" loss which increases at high firing rates. These characteristics and the "total efficiency loss" curve shown in the figure are very representative of many industrial boilers and should also adequately represent process heaters. Lowest losses (highest efficiencies) occur over the range of firing rate from approximately 50 percent to 80 percent of capacity. Operating a

heater in this range as much of the time as possible would therefore be desirable from a fuel efficiency standpoint.

Later in this manual, the basic approach and test equipment necessary to identify the point of maximum efficiency will be described in detail. Once this information is available for a particular heater, it can be used together with NO_x emissions measurements to determine the optimum heater operating practice for high efficiency and reduced NO_x.

The efficiency improvement for a heater at each firing rate will depend on the reductions in stack O_2 possible and the stack temperatures. To aid in determining the actual efficiency improvements, Figure 1-4 gives the approximate percent efficiency improvement* corresponding to each 1 percent reduction in excess air. Since reductions in O_2 will be measured directly, use Figure 1-1 to convert stack O_2 to excess air and then determine the efficiency improvement at the proper stack temperature. For example, if the stack O_2 were reduced from 6 percent to 3.5 percent, from Figure 1-1 it is determined that the excess air dropped from 40 percent to 20 percent, a 20 percent total change. If the stack temperature were 477 K (400°F), the efficiency improvement was 20 times 0.058 or 1.16 percent.

Reductions in stack temperature will also generally occur as the O_2 is lowered. To account for this effect, perform the previous calculation using the initial stack temperature and add to this improvement the efficiency improvement obtained from Figure 1-5. This additional improvement from Figure 1-5 is the effect of reduced temperature and is determined using the final lower excess air level. To illustrate, if in the previous example, the

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*Note that percent efficiency improvement as defined here means the difference between thermal efficiency of the unit in the modified or adjusted condition and the thermal efficiency in the unadjusted condition. This term should not be confused with the fractional efficiency improvement used in some publications. The fractional efficiency improvement is defined as the percent efficiency improvement divided by the efficiency of the unit in the unadjusted condition times 100. The fractional efficiency improvement is often labeled "percent efficiency improvement" and, therefore, the reader must be alert to the difference. If, for example, the unmodified heater efficiency is 80 percent and the modified or adjusted unit efficiency is 82 percent, the percent efficiency improvement would be 2 percent while the fractional efficiency improvement would be (2/80) x 100 = 2.5 percent.

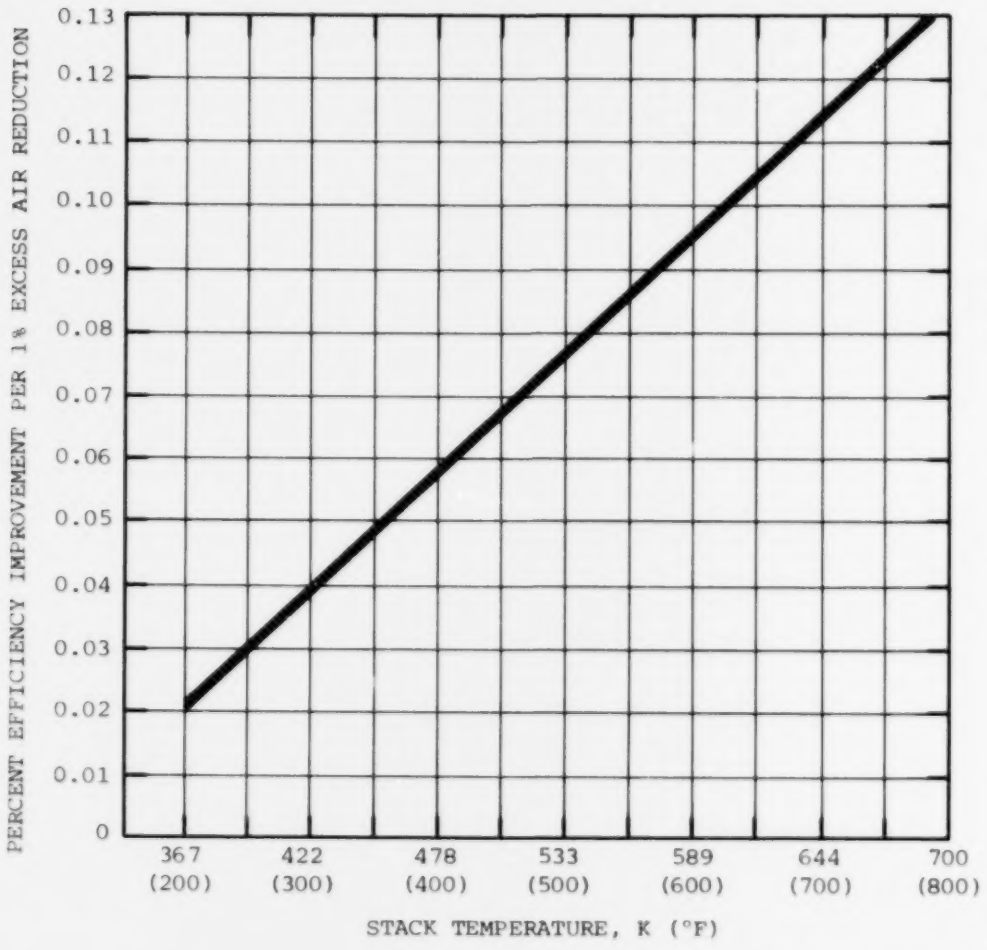

Figure 1-4. Curve showing percent efficiency improvement per every one percent reduction in excess air. Valid for estimating efficiency improvements on typical natural gas, No. 2 through No, 6 oils and coal fuels.

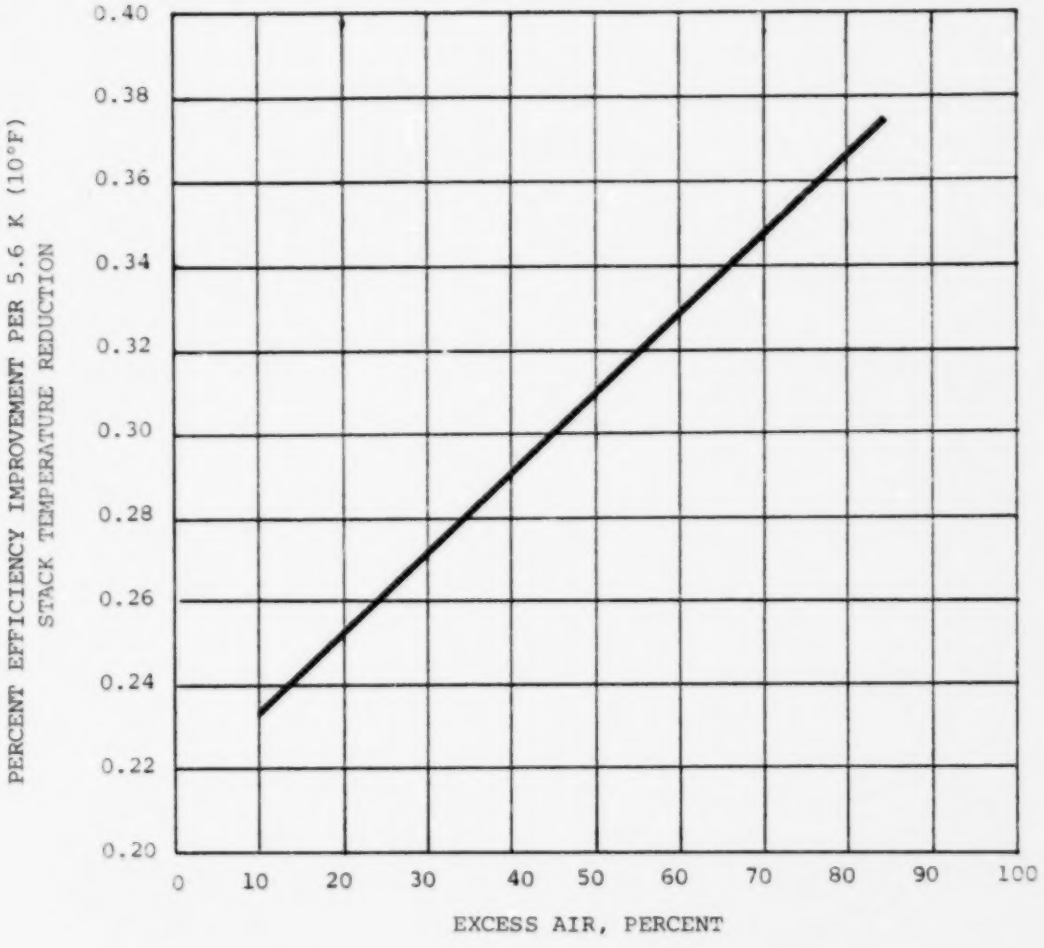

Figure 1-5. Curve showing percent efficiency improvement per every 5.6 K (10°F) drop in stack temperature. Valid for estimating efficiency improvements on typical natural gas, No. 2 through No. 6 oils and coal fuels.

stack temperature dropped from 477 K (400°F) to 460 K (370°F) as the O_2 were lowered from 6 percent to 3.5 percent, the effect due to the 17 K (30°F) lower stack temperature would be 3 times 0.252 which equals 0.76 percent. The total improvement in efficiency is then 1.16 plus 0.76 for a total improvement of approximately 1.92 percent. Figures 1-4 and 1-5 can be used to estimate efficiency improvements achieved at constant firing rates on natural gas, #2 through #6 oils and common bituminous and subbituminous coals.

Some heater operators who use these guidelines may find that their heaters' efficiencies can be improved by 1 or 2 percent which might at first seem to be a small improvement having little effect on total fuel costs. However, even for the smallest heaters, these seemingly small improvements can lead to significant annual fuel savings which easily justify the time and effort spent in achieving the improvements. Consider, for example, a 3.5 MW_{th} heater that is operated year-round with an average annual loading of one-half full capacity. If the efficiency is improved by 2 percentage points over the heater operating range, the annual fuel consumption will decrease by 2.4 percent, assuming the unimproved heater efficiency is approximately 80 percent. (Percent fuel reduction equals efficiency improvement times 100, divided by the improved efficiency.) If the heater is fired with No. 6 oil costing $4.00 per million Btu ($13.70/MW-h), the annual fuel savings would be about $5,000. The annual savings for a comparable gas-fired heater would be approximately $6,800 based upon firing gas costing $5.42 per million Btu ($18.50/MW-h). For larger heaters, this savings would increase in proportion to the size of the heater ($50,000 for a 35 MW_{th} heater and so on).

SECTION 2.0

SUMMARY OF RESEARCH TEST PROGRAM

2.1 OBJECTIVES AND SCOPE OF FIELD TEST PROGRAM

The objective of the research test program was to investigate advanced combustion modification concepts requiring relatively minor hardware modifications that could be used by operators and/or manufacturers of selected industrial process equipment to reduce emissions and to improve thermal efficiency. The investigation was to be performed for equipment in which the modifications would be most widely applicable and of the most significance in mitigating the impact of stationary source emissions on the environment. Another objective was to assess the feasibility of these modifications to the extent that they could be readily adopted by the fuel burning equipment manufacturers. The path to this goal included concept definitions, economic and technical assessment, subscale performance evaluation tests, cost/benefit analysis, equipment modification or retrofit, performance evaluation tests, and preparation of final reports and instructional guidelines.

2.2 PAST WORK

The first program in which combustion modifications were attempted on process heaters is reported in EPA-600/7-79-015a (Ref. 2). The objective of that effort was to investigate the effectiveness and applicability of combustion modifications involving only operating variable changes as means of improvement in thermal efficiency and for emissions reduction in industrial combustion equipment.

The program scope provided for tests on 22 industrial combustion devices representative of kilns, process furnaces, boilers, stationary engines, and gas turbines in industrial use. Combustion modifications evaluated, where possible, included lowered excess air, staged combustion,

reduced air preheat, and burner register adjustments. No hardware modifications were attempted, however. All experiments involved only operating changes.

In general, the results indicated that combustion modifications could be applied to industrial combustion equipment, but reductions available varied significantly for different types of devices. Five natural draft process heaters which fired refinery gas were tested. Air register adjustments, burners-out-of-service, and lowered excess air produced NO_x reductions ranging from 8 to 27 percent below baseline levels. (Baseline NO_x emissions ranged from 76 ppm to 116 ppm, dry basis, corrected to 3 percent O_2.)

As a part of a follow-on combustion modification program (EPA Contract No. 68-02-2645) tests on a subscale natural draft process heater firing natural gas, No. 2 oil, No. 6 oil, and shale oil were made. These tests were the subject of the final report (Ref. 3).

Several combustion modifications, most of which involved minor or major hardware changes, were evaluated during these tests. They included the following:

- Low-NO_x burners
- Staged combustion air through floor lances
- Staged combustion air through a central cylinder
- Steam injection
- Flue gas recirculation
- Altered fuel injection geometry
- Lowered excess air

2.3 PROCESS HEATER TEST PROGRAM

Following the subscale work, a location was sought which would permit the application of combustion modifications and, in particular, the installation of staged combustion air lances, on an operating process

heater. A natural draft vertical cylindrical crude heater containing six burners, capable of combined fuel firing, of the same design as those previously tested at the subscale facility was found.

An initial series of tests was conducted to determine heater performance over a range of operating variables such as excess air, load, and air register settings for various fuel types. The tests were similar to tests mentioned earlier in that no hardware modifications were made to effect combustion modifications. For some tests firing refinery gas, steam was injected through the oil-atomizing system and its effect on NO_x emissions was assessed.

Once the performance of the heater was documented over its normal range of operating parameters, staged combustion air was implemented. A prototype system, constructed largely of polyvinyl chloride pipe, fittings, and valves with twenty-four stainless steel lances (four per burner) was built. The system shown in Figure 2-1 was designed to provide maximum flexibility and flow control for minimum cost. Figure 2-2 is a schematic of the staged combustion burner showing the air lance placement. The heater was then re-evaluated over the same ranges of operating parameters. During testing of the staged air system several new parameters were varied. These included burner stoichiometric ratios, staged air insertion height, and staged air lance orientation. An optimum low-NO_x operating condition was defined as the configuration at which the lowest NO_x concentrations were obtained while still permitting stable heater operation without a significant increase in CO emissions. This condition was defined for gaseous fuel and for a 50/50 mixture of No. 6 oil and gas.

A 30-day test was then conducted with the staged air system in continuous operation firing refinery gas at the optimum low-NO_x condition. System performance and durability were evaluated as well as the ability to maintain steady heater operation at the low-NO_x condition. At the completion of the long-term test a permanent system was designed. This system was intended to be suitable for a typical furnace of the same type as that tested on this program.

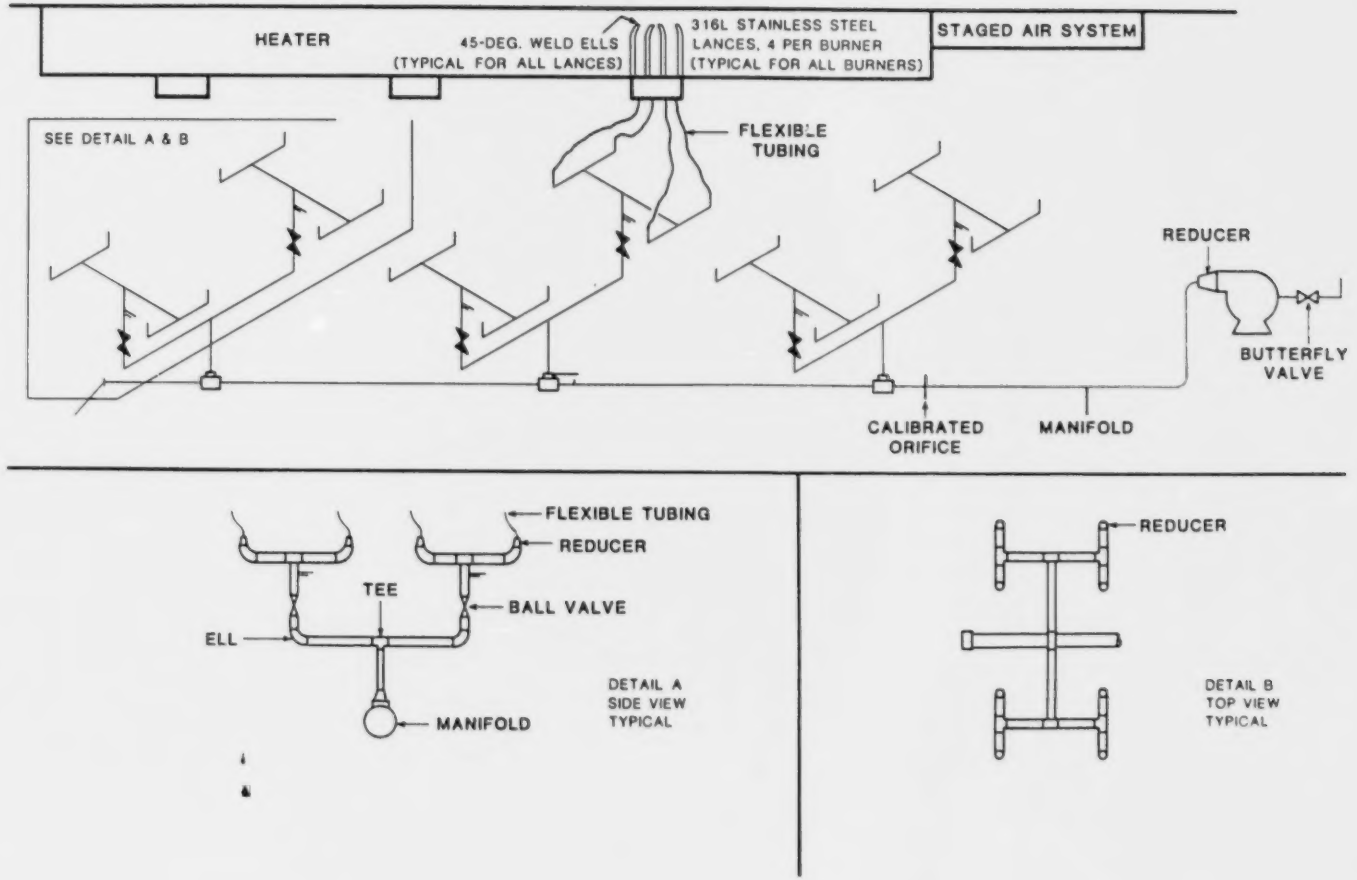

Figure 2-1. Flow schematic of staged combustion air system for a natural draft process heater.

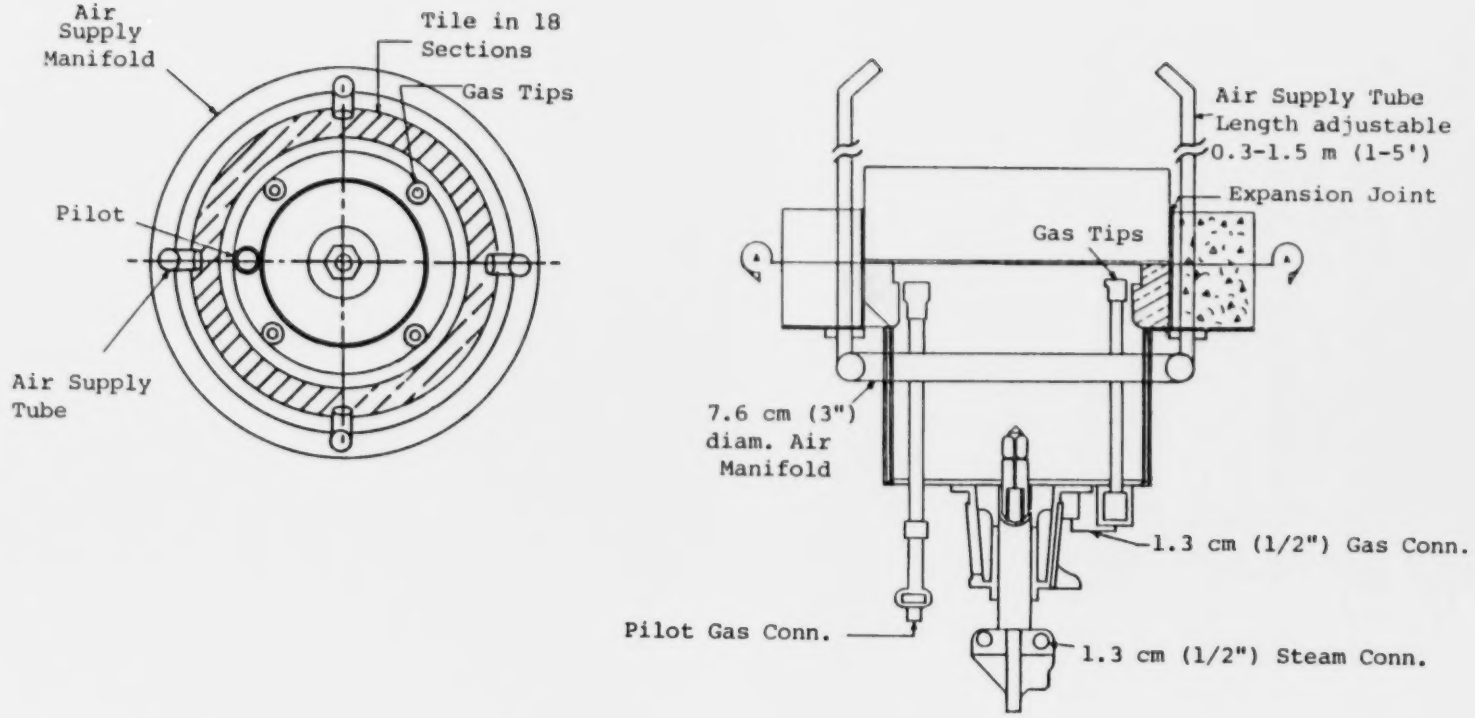

Figure 2-2. Schematic of staged combustion burner.

The cost effectiveness, based on the permanent system design, of the staged combustion modification was evaluated for the gaseous fuel and for the combination fuel, and also at two levels of stack oxygen. The cost effectiveness is given in Appendix A.

A summary of the significant results obtained during the test program is given in Table 2-1. A detailed final report covering the research activities at this heater has been submitted to the EPA for publication (Ref. 4).

2.4 CONCLUSIONS

The following conclusions were drawn from the field testing and analyses performed on this project.

1. Lowered excess air and staged combustion air reduced NO_x emissions on a natural draft vertical cylindrical process heater firing either gas only or No. 6 oil and gas.

2. Steam injection was not effective in reducing NO_x emission firing refinery gas.

3. In a long-term test, the combination of staged combustion air and lowered excess air reduced NO_x emissions by 71 percent below a baseline of 130 ppm firing refinery gas while decreasing fuel consumption by nearly five percent.

4. Some form of automatic stack O_2 control is necessary in order to maintain the desired low stack oxygen content (~2 percent O_2, dry) which produced optimum low NO_x operation.

5. Without any such automatic system, the staged air system operated at a normal overall excess air level (~4 percent O_2, dry) when firing refinery gas in a long-term test and reduced NO_x emissions by 60 percent below the 130 ppm value while decreasing fuel consumption by about 0.2 percent.

6. The staged combustion air system can function effectively and continuously with little operator attention and little lance deterioration over a 30-day period.

TABLE 2-1. SUMMARY OF RESULTS OF COMBUSTION MODIFICATION TESTS ON A PROCESS HEATER

Heat Input MW	Fuel Type	Baseline NO_x ng/J	Baseline NO_x ppm dry at 3% O_2	NO_x Reduc. From Baseline %	Change in Fuel Cons. %	Combustion Modification
10.4	Ref. gas[1]	66	125	60	-0.2	SCA[2]*
10.4	Ref. gas	66	125	71	-4.8	SCA + LEA[3]*
9.0	Ref. gas	54	105	15	-2.8	LEA
13.7	Ref. gas	61	120	2.5	+2.2	Steam inj.
13.2	No. 6 oil + Ref. Gas	114	212	34	-0.6	SCA
13.1	No. 6 Oil + Ref. Gas	115	214	53	-4.8	SCA + LEA
13.1	No. 6 Oil + Ref. Gas	115	214	28	-3.0	LEA

[1] Ref. gas = Refinery gas

[2] SCA = Staged Combustion Air

[3] LEA = Lowered Excess Air

* Based on results of a 30-day test

7. The staged combustion air system is expected to be applicable to most types of refinery heaters, whether forced draft or natural draft and whether vertical or horizontal. The cost effectiveness is likely to be site specific, however.

8. Predictions based on subscale tests for NO_x reductions on the order of 35 percent for normal O_2 and 50 percent for lowered O_2 on a natural draft process heater with staged combustion air are expected to be valid for 100 percent No. 6 oil firing in a full scale heater.

9. The cost of staged combustion air on a natural draft process heater applied at normal stack O_2 is calculated as $2636/Mg NO_x reduction for a 16.1 MW heater and decreases to $1934/Mg at 147 MW heat input.

10. The cost of staged combustion air combined with lowered excess air on a natural draft process heater applied at 2 percent stack O_2 is calculated as $1089/Mg for a 16.1 MW unit. The cost effectiveness becomes negative for a 147 MW unit indicating a savings associated with the combined modifications.

SECTION 3.0

COMBUSTION ADJUSTMENTS TO PROCESS HEATERS

3.1 ESTABLISHING OPTIMUM OPERATING CONDITIONS

To establish the optimum operating conditions on a natural draft process heater such as excess air level, air register settings, and stack damper position, one should be able to accurately measure stack oxygen, NO_x and carbon monoxide concentrations, stack temperature, tube skin temperatures, and furnace draft (preferably at a minimum of three elevations in the heater--at the firebox, the convection section inlet or bridgewall, and the stack). These measurements allow the operator to maximize heater efficiency by reducing the excess air (stack oxygen) to the minimum amount which can be maintained without causing combustibles (carbon monoxide) to appear in the stack gases. The effect of the reduction of excess air on heater thermal efficiency is discussed in Section 1.2. Reducing the excess air will generally affect the stack gas temperature, as well. A change in stack gas temperature also affects heater thermal efficiency as discussed in Section 1.2 and, therefore, is an important parameter to be measured so that the efficiency improvement may be quantified.

Lowering the excess air to this minimum value also tends to lower NO_x emissions since it reduces the amount of atmospheric nitrogen coming into contact with the flame. Measuring the NO_x concentration (NO_x equals the sum of the nitric oxide (NO) and the nitrogen dioxide (NO_2) concentrations) is thus important to quantify the amount of emission reduction obtained by adjusting the heater. Measurement of NO_x is not necessary to establish the optimum operating condition but is desirable for quantifying the NO_x emission reduction achieved.

Also important in a natural draft heater when making air adjustments is the draft profile. The heater should be maintained at a negative pressure throughout in order to avoid flashback at the burners and to prevent the

escape of toxic and flammable combustion gases to the suroundings through cracks, ports, etc. Normally, the pressure at the top of the firebox or bridgewall is the highest in the heater (though still less than ambient pressure). This pressure becomes another operating limitation as the excess air level is reduced in addition to the appearance of combustibles in the stack gas. Once the excess air has been reduced to the point at which the bridgewall draft is nearly zero (for example, less than 0.01 inch H_2O gauge), further reductions in excess air without changing the burner air register settings could upset heater operation. (It is assumed here that changes in excess air levels are accomplished in normal situations by adjusting only the stack damper position and that the air register settings are not normally changed except to accommodate large variations in the heater load or throughput.)

If the bridgewall draft limitation is reached when reducing the excess air well before the point at which combustibles begin to occur in the stack gas, the operator may wish to close the burner air registers somewhat in order to increase the furnace draft. At this point changes must be made slowly and carefully with constant attention to flame appearance. The heater will be operating with a more lazy, wandering flame which may be less stable and may be impinging on the process tubes. The operator will also need to be aware of the stack oxygen and CO (carbon monoxide) concentrations at this time. In closing the air registers, it is usually preferable from a NO_x emissions standpoint to start with the primary* air register and then proceed with the secondary air register (followed by the tertiary air register if so equipped). Registers should always be left at least slightly open to avoid air starvation. It may be necessary to partially close only one set of registers to achieve the desired increase in furnace draft. If there is more than one burner, some burner register settings may differ from others depending on

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*Primary air is defined here as that air which comes most directly in contact with the injected fuel. Note that in a gas-firing burner the real primary air is actually entering through the air registers labeled "secondary" air registers. For the purposes of this discussion, those registers should be treated as primary air registers. Similarly, the innermost ring of registers, usually labeled "primary" air registers should be treated as secondary air registers in a gas-firing situation.

the condition of burner tips, burner tile, etc. It must be kept in mind, however, that the stack damper may have to be reopened slightly in order to draw the same amount of air through the heater that was being drawn prior to closing the register(s).

The operating condition which results in the lowest stack oxygen level and stack temperature (without affecting the heater feed rate and while maintaining negative pressures throughout the heater) must also result in radiant section tube skin temperatures which are well within the limitations of the tube materials and/or the process constraints. Significant local increases in tube skin temperatures could cause coking of the process fluid or tube failure. It is thus essential that tube skin temperatures, especially in the vicinity of the flame, be monitored throughout any adjustment procedure. Remember that changes in flame appearance can be an indication of the changes in the tube temperatures caused by a combustion adjustment.

Once the condition is reached at which stack O_2, NO_x, and stack temperature have been optimized with respect to CO emissions, heater draft profile, and tube skin temperatures, the proper operating condition has been reached for that particular heater feed rate. It then remains to determine the optimum operating conditions at several other feed rates covering the normal operating range of the heater.

The NO_x emissions resulting from a heater at various stack oxygen levels at varying process rates are shown in Figures 3-1 and 3-2 for gas firing and for gas/No. 6 oil firing, respectively. These data were collected from the test site discussed in Section 2.0. Although baseline NO_x emissions are higher for oil fuels, the general shapes of the curves are similar for both oil and gas fuels. These characteristic curves should be developed for each individual heater in order to compare results each time the unit is adjusted. Ideally, for constant fuel and feed composition, each time the heater is returned to the same set of operating conditions (i.e., fuel and feed flow rates, feed inlet and outlet temperatures and pressures, fuel temperature and pressure, stack oxygen, register settings and furnace draft, combustion air temperature and humidity), the same NO_x emissions will result. Naturally, it is never possible to duplicate a set of operating

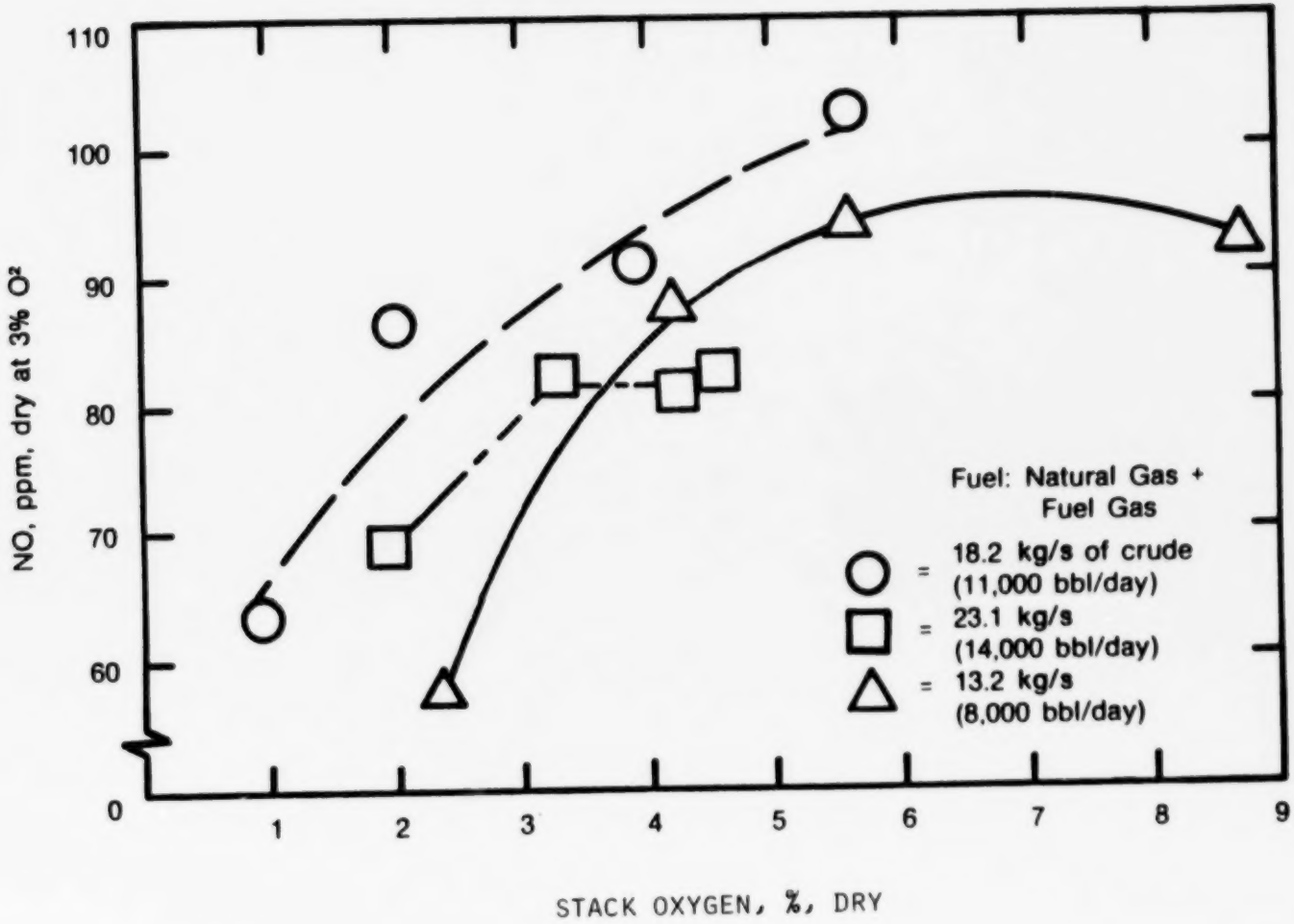


Figure 3-1. NO emissions at three different loads as a function of stack oxygen for a natural draft process heater firing a natural gas/refinery gas mixture.

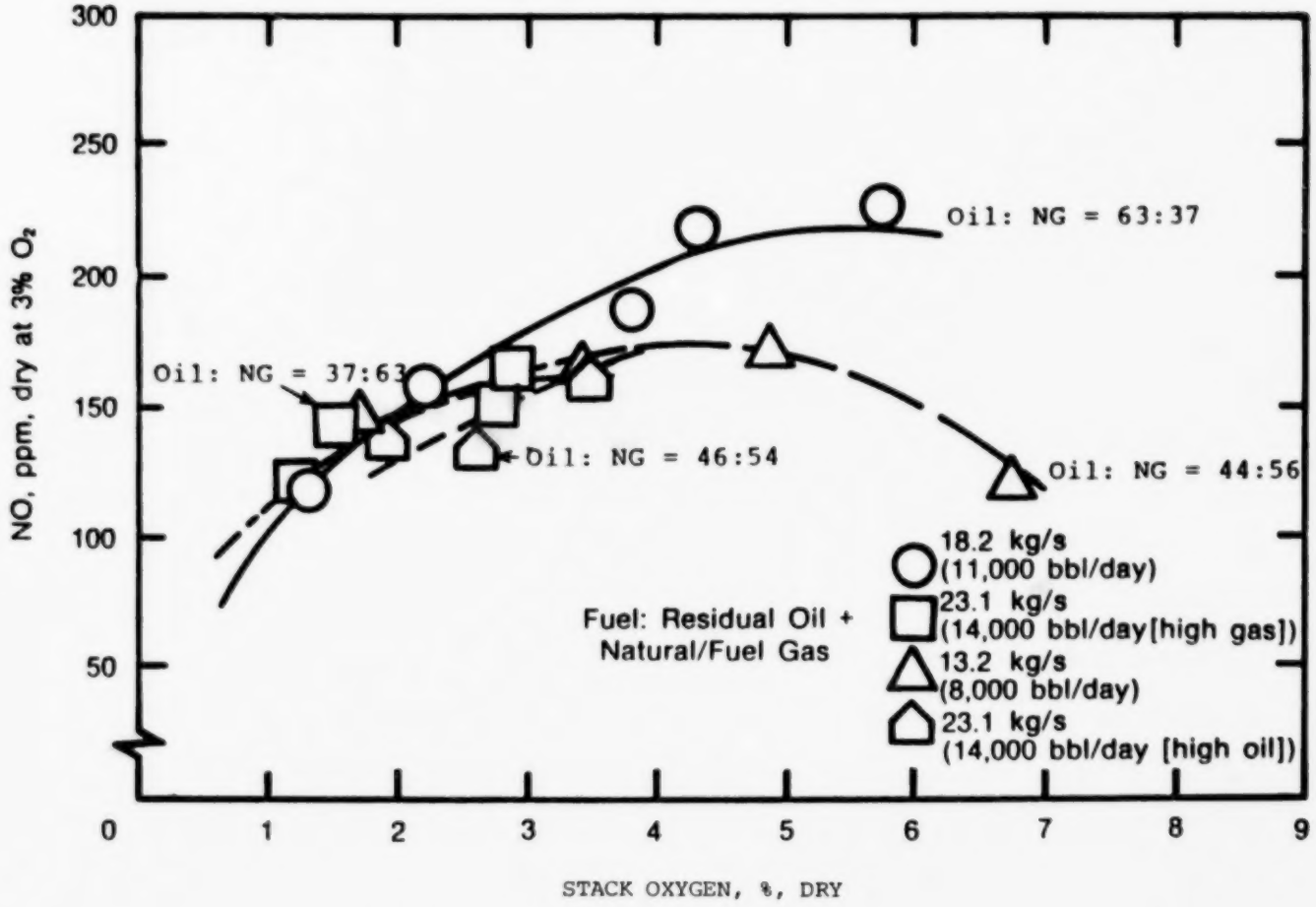


Figure 3-2. NO emissions at three different loads as a function of stack oxygen for a natural draft process heater.

conditions exactly; however, a discrepancy of more than about 5 percent in NO_x emissions when attempting to reproduce a past test condition usually indicates that some operating parameter has not been correctly set.

3.2 STACK SAMPLING INSTRUMENTS AND TECHNIQUES

3.2.1 Stack Oxygen Measurement

The concentration of oxygen in heater stacks may vary from about 2 percent to 10 percent or more, depending on heater design, type of fuel, burner adjustment, and firing rate. Typically, the lowest practical level of oxygen offers the highest efficiency and lowest rate of emissions.

Oxygen can be measured with a portable analyzer if the heater is not equipped with a permanent meter. Reasonable accuracies also can be obtained with an Orsat analyzer if it is operated by an experienced technician using fresh chemicals. Other hand-held chemical-absorbant type analyzers are commercially available, too. Note that excess-air levels also can be determined from measurements of carbon dioxide in the flue gas (see Section 1.2).

Keep in mind that proper calibration of stack instruments is essential for accurate readings and successful heater adjustment. Follow the recommended calibration procedure for the instrument and adjust the frequency of calibration as necessary to minimize drift, and be sure to recalibrate your equipment before beginning heater tests.

When calibration gases are required, cross-check the new samples, when delivered, against older ones, to catch any errors in the calibration gas itself. For absorption-type analyzers, make sure the chemicals are fresh by establishing a routine for renewing absorbants based on the number of samples analyzed and the age of the chemicals.

3.2.2 Carbon Monoxide Measurement

On heaters, carbon monoxide is the primary indicator of incomplete combustion and usually determines the lowest practical level of excess oxygen. Note that the concentration of CO in the flue gas should not exceed 400 ppm--the limit established by some city ordinances, industry codes, and insurance organizations--once the final adjustments are made. When performing

tests, occasional CO levels of up to 1000-2000 ppm are acceptable, provided adequate heater monitoring and flame observation are possible to assure stable conditions. But use caution at these levels: Further reduction of excess air causes a rapid increase in CO and other combustibles, which can lead to smoking, flame instability, furnace pulsation, and possibly an explosion.

As a rule, one does not observe significant CO emissions from natural draft gas-fired heaters until the stack O_2 concentration is below about 0.5 - 1.0 percent (dry basis). On oil-fired heaters CO will begin to appear in high concentrations at about the same O_2 concentration that causes visible smoking. This is typically about 1.0 - 1.5 percent (dry basis).

By measuring CO you can be sure burners are operating properly, a prerequisite for meaningful testing. Your CO analyzer should be capable of detecting from about 100 to 2000 ppm. While Orsat analyzers traditionally have been used for determining CO, difficulties in accurate reading of concentrations less than 1000 ppm have increased the use of hand-held, length-of-stain-type detectors. Such color-sensitive tubes reportedly provide the necessary sensitivity and measurement range. Portable or permanently mounted electronic instruments also are available. Their ability to measure CO continuously is desirable when making burner adjustments since CO excursions may not be detected with occasional spot readings.

3.2.3 Sampling Techniques

Most of the oxygen and CO analyzers discussed above require that a sample of flue gas be withdrawn from the stack and delivered to the instrument. Some analyzers require a continuous flow of sample until a stable reading is obtained; others need only a single, small-volume sample. Exceptions are in-stack instruments with detector elements located in the flue-gas stream. Regardless of the analysis technique, the portion of gas analyzed must be representative of the total gas stream.

Location of the sampling site can be as important as the selection of the proper measurement device. Sample locations immediately downstream of bends, dampers, or induced-draft fans should be avoided. Gases in such areas can stratify or form pockets, leading to errors, especially when samples are withdrawn from a single point in the duct.

When a single-point probe is to be used, compare readings at several points in the duct first to find the most representative probe location. When existing ports are not satisfactory, drill or cut out new ports. Remember, unless you get truly representative data, your testing program will be of little value.

Flue gas temperatures also are subject to stratification in ducts, and a representative location of thermometers or other temperature sensors should be verified.

3.3 FLAME APPEARANCE

The appearance of a process heater's flame offers a good preliminary indication of combustion conditions. It is difficult to generalize the characteristics of a "good" flame, because of variations due to burner design, and because a certain amount of operator preference is involved.

For other types of combustion equipment, flames with a definite appearance usually have been sought. Examples: Short, bright, crisp, and highly turbulent oil flames; blue, slightly streaked, or nearly invisible gas flames. Stability of the flame at the burner and minimum furnace vibration also are universally desirable.

Too often, the good flame appearances described above are achieved by operating with stack oxygen levels higher than are necessary for safe, clean firing. When operating with the lowest practical amount of oxygen, approximately the same amount of heat energy is released in the furnace for a given amount of fuel heat-energy input. However, less energy is wasted in heating excess air, which is not required for combustion. In addition, the reduced oxygen level leads to increased flame length because it takes more time for the fuel to burn completely. The result typically is a flame that:

1. Actually grows in size, and fills the furnace more completely.

2. Exhibits a lazy, rolling appearance. Instead of intense, highly turbulent flames, low-oxygen flames may appear to move somewhat more slowly through the furnace.

3. Has an overall color that may change as excess oxygen is decreased. Natural-gas flames, for instance, become more visible or luminous with yellow or even slightly hazy portions. Oil flames become a darker yellow or orange and may appear hazy in parts.

Safety, reliability, and satisfactory particulate emissions can be achieved with low-oxygen firing, even though these flame characteristics are, for the most part, contrary to flame conditions traditionally desired by operators. Operation at a lower stack oxygen level requires operator attention during set-up. The level of attention required varies depending on the process variables, fuel variability and the stringency of oxygen control. In general, it is good policy to make daily measurements of the stack oxygen content for the operational log. Flame impingement on process tubes should be avoided at all times for the reasons discussed earlier.

3.4 HEATER PERFORMANCE EVALUATION AND MONITORING

After heater operation is optimized, there are two things necessary to maintain high efficiency and low emissions:

1. Spot-check combustion efficiency on a daily or weekly basis, to warn of problems before much fuel is wasted or extensive maintenance is required.

2. Conduct a comprehensive inspection and performance check of heater equipment periodically, to identify any necessary maintenance or repairs.

A spot check of combustion conditions using stack measurements of oxygen (or CO_2), CO, and temperature is an effective method of gaging performance. Take these measurements when the heater is operating at steady-state conditions and compare them to those obtained during the previous heater-adjustment tests. These data help identify any deterioration in combustion efficiency, as well as the possible causes. In many plants, efficiency-related data are checked on a daily basis, sometimes during each work shift.

Changes in the level of stack oxygen might be caused by problems in the fuel-supply system, or might reflect changes in fuel properties. Other possibilities include deterioration in furnace walls, leakage through ports, excessive tube fouling, or changes in atmospheric conditions. If stack oxygen

has remained constant, but CO has increased, fuel composition may have changed, or there may be a problem with burner operation. Examples: Oil-tip plugging, oil-atomizing-system problems, burned-off or improperly adjusted burner parts.

If stack temperatures have increased by 11 K (20°F) or more, but stack oxygen and CO have remained the same, excessive tube fouling may be the problem.

While spot checks of combustion conditions are valuable for identifying efficiency degradation, long-term performance monitoring, including documentation in a heater log, is a more effective means for ensuring peak efficiency. The objective of such a monitoring program is to document deviations from desired performance levels as a function of time.

As noted above, this information should be obtained regularly, when the heater is operating at constant load. Data taken during load changes or under conditions of fluctuating load are inconsistent, and are therefore of little value in assessing unit efficiency. Control response, however, should be examined during transient operation.

If a widely fluctuating load is typical, you may have to make special arrangements to achieve a constant feed rate to the heater.

The number and frequency of readings needed depends on the size and complexity of your equipment and the manpower that can be justified for collecting and analyzing data. Hourly readings are recommended as a check on general performance. These readings assure that the unit is operating normally and that safety and other mechanical devices are functioning properly.

For some smaller installations, it may seem a continuous oxygen analyzer cannot be justified. For these installations, a portable oxygen analyzer with a CO analyzer in the same package would provide a more reliable and accurate measurement than an Orsat analyzer at approximately same cost. Additionally, measurements could be made during routine operator inspections after installation of a stack sampling line.

When constant load conditions are difficult to obtain, put less emphasis on recording efficiency-related data in the heater log and more on conducting performance checks--monthly for small units, biweekly for large heaters.

Record all pertinent data to obtain maximum benefit from your testing program. A record of heater operating conditions and stack measurements not only documents the heater's efficiency and emission characteristics, but also permits future comparisons to help diagnose any problems. Test data should be recorded on prepared data-sheet forms similar to that shown in Figure 3-3 and should include the following items:

1. Heater identification, fuel type, date of tests, names of operating personnel involved.

2. Process fluid and fuel conditions (flow rates, pressures, temperatures), to document heater firing rate and process throughput.

3. Combustion control system and burner settings.

4. Furnace pressures, temperatures, damper settings, combustion air temperature, pressure, and humidity.

5. Stack measurements--oxygen, carbon dioxide, carbon monoxide, temperature. Note sample-probe position.

6. Relevant comments on flame appearance and furnace conditions.

7. Permanent changes made to combustion controls or burner settings.

The actual heater readings included will, of course, depend on available instrumentation. Make sure that adequate data are obtained, so exact heater operating conditions can be repeated for comparison purposes. Also, record readings only after steady-state heater conditions are attained. This usually is indicated by constant stack temperature, fuel input, and feed characteristics (pressure and temperature and flow rate). Stable stack oxygen readings are a good indication of stable fuel and air flows.

Test No._____ Date_____ Location_____ Engr._____

Unit No._____ Fuel_____ Capacity_____

Unit Type_____ Burner Type_____

Test Description:_____

1. Test Number					
2. Date					
3. Time					
4. Load x 10^6 Btu/hr					
5. Process Rate (bbl/d)					
6. Crude T_{in} (°F)					
7. Crude T_{out} (°F)					
8. Crude P_{in} (psig)					
9. Crude P_{out} (psig)					
10. Reabsorber Gas in (10^3 scf/d)					
11. Natural Gas in (10^3 scf/d)					
12. Fuel Oil T in					
13. Fuel P/Steam P (psig)					
14. Secondary Air Flow P					
15. Staging Height (ft)					
16. Secondary Air Damper, % open					
17. Secondary Air T (°F)					
18. Stack T (°F)					
19. Fuel Oil T (°F)					
20. Stack Damper (% open)					
21. Bottom Furnace P (iwg)					
22. Convective P (iwg)					
23. Stack P (iwg)					
24. Air Registers (% open)					
25. Crude API Gravity					
26. Flame Observations					
27. Other Observations					

Figure 3-3. Unit Operating Data

SECTION 4.0

STAGED COMBUSTION AIR MODIFICATION

The principle of staged combustion is not a new one. It has been used as a NO_x reduction technique on utility and industrial boilers and steam generators for a number of years. The recent interest in applying NO_x reduction technology which permits safe, reliable operation at minimum additional cost to other industrial combustion devices provided the motivation behind the design of a staged air system which would be applicable to a large number of refinery process heaters. Process heaters as well as several other industrial device types, had been determined to contribute significantly to nationwide NO_x emissions in addition to consuming large amounts of energy in the form of fossil fuels.

Reference 3 showed that natural draft process heaters consumed 1.3×10^{15} Btu (1.37×10^{18} J) annually while emitting 103,000 tons/y (93.4×10^{9} g/y) of NO_x. This energy consumption represents over half of the total annual energy consumption by all U.S. refineries. To put these numbers in perspective the total annual energy consumption by all of the industrial boilers in the U.S. was estimated in Reference 5 to be 6.09×10^{15} Btu (6.43×10^{18} J). Thus natural draft process heaters consume about one-fifth of the energy consumed by all domestic industrial boilers - a significant fraction. NO_x emissions from industrial boilers were estimated by the same source to be 2,011,000 tons/y (1.8×10^{12} g/y). Thus, natural draft heaters produced about one-twentieth of the total NO_x emissions produced by industrial boilers. (The reason for the disproportionately low-NO_x emissions from process heaters relative to industrial boilers is probably due primarily to the fact that many boilers burn high-nitrogen fuels such as coal or residual oil whereas most process heaters burn gas fuel, some burn heavy oil and none burn coal.) Although producing considerably less NO_x than industrial boilers, natural

draft process heaters as a class of industrial combustion devices emit more NO_x than any other single class of industrial combustion devices except cement kilns.

The staged combustion air design discussed in this section is expected to be applicable to most types of natural draft process heaters as well as some types of mechanically drafted heaters. It was developed with simplicity, ease of installation particularly on existing units, reliability, and low cost as the major design considerations. The following sections discuss the design and operation of the staged air system. Included in the section on design is information on applicability, sizing the pipes and blower which comprise most of the system, instrumentation required, and safety features. The following section on operation of the system includes details of startup, routine operation, and recommended maintenance procedures.

4.1 SYSTEM DESIGN

The staged combustion air lance system flow schematic is presented in Figure 4-1. Basically, the system provides combustion air downstream of the fuel injection plane of each burner by means of a forced draft blower. The air is injected into the firebox through pipes or "lances" which penetrate either through the floor of a vertically fired unit or the walls of a horizontally fired unit. The introduction of air downstream of the burners permits fuel-rich operation at the burners with as little as 60 percent of the theoretical air required for complete combustion. The amount of the combustion air that is injected through the staged air lances is enough to provide the remainder of the theoretical air requirement plus the amount of excess air necessary to eliminate combustibles in the flue gas and provide a good flame.

The system was designed for a vertical cylindrical heater with six natural draft John Zink DBA-22 burners. The heater had a maximum thermal input capability of 16 MW (55×10^6 Btu/hr). The staged air system had the capability of controlling the air flow to each burner by means of ball valves and the lance height above the furnace floor was adjustable. These features,

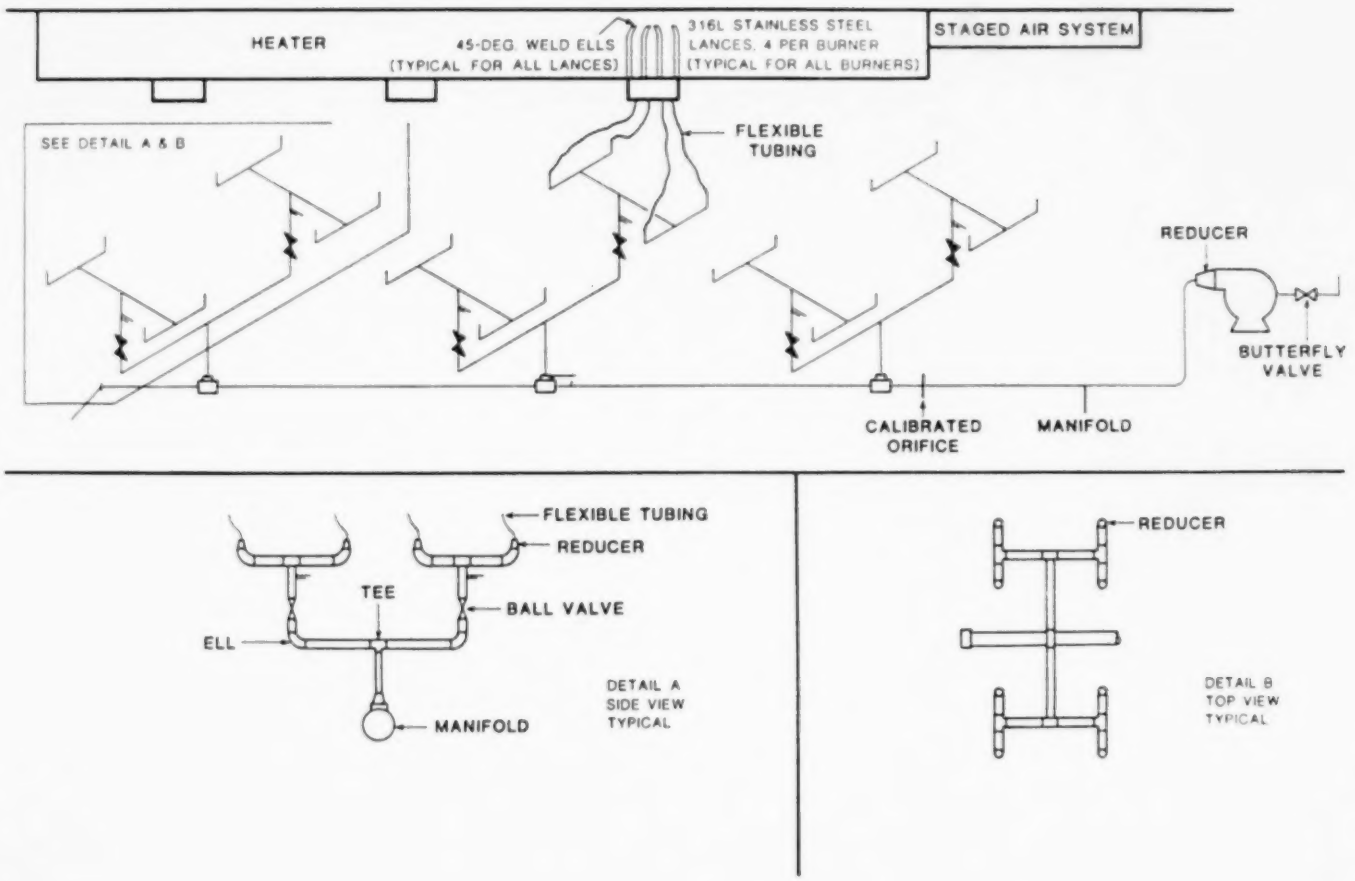


Figure 4-1. Flow schematic of staged combustion air system for a natural draft process heater.

although desirable, are not necessary in a working system. They were used to allow flexibility so that firing conditions could be optimized to the greatest degree possible in the prototype system.

Provision should be made in the design of the system to vary the lance height above the furnace floor. During the system checkout testing, the firing conditions can be optimized for each specific heater design and operating condition. After the optimum configuration has been determined, the system can be hard plumbed, if desired.

The height of the staged air lance tips was 1.2 m (4 ft) above the plane of the burner gas tips. This height was found to give the best NO_x reductions for both gas-firing and gas/oil-firing in the heater tested.

4.1.1 Applicability of the Staged Combustion Air Modification

The combustion modification technique of staged combustion air has been assessed on a vertically fired natural draft process heater for thirty days firing refinery gas. The modification has been applied for short-term tests (up to 12 hours) on this unit when firing No. 6 oil and refinery gas in approximately equal proportions by heat input.

Ultimately it is expected that this modification could be applied to virtually any type of process heater, however the fan requirement, the NO_x reduction potential, and the efficiency implications are all likely to be site specific. This is true because of the wide variety in heater designs currently in use. Temperature and pressure/draft profiles may differ significantly from those measured at the prototype site and may have significant effects on the NO_x reduction potential and efficiency impact of staged combustion air.

For heaters which are mechanically drafted, this combustion modification technique may prove to be very cost effective since a separate staged air fan would probably not be required. The initial design and installation of a staged air system would likely be more complex for that type heater, however, than they were for the natural draft unit.

A horizontally fired heater would probably require that lances be placed horizontally into the firebox. In that case lance skin temperatures

would become more critical since they may be high enough to cause the lances to droop. Some vertically fired heaters may be more easily modified by means of horizontal lances, also, due to ground clearance limitations (the distance between the heater floor and the ground limits the staged air lance height above the burner). In that instance the modification is similar to overfire air or "NO_x ports" which are already in use on many industrial and utility boilers.

It is expected that staged combustion air will be applicable to all process heaters regardless of fuel type although optimum lance placement and orientation may be different when burning 100 percent No. 6 oil fuel from the configuration used for refinery gas fuel and the gas/oil mixture.

In any situation where key parameters are different from those of the test unit (e.g., fuel type, pressures, temperatures, air velocities, and mixing patterns) this staged combustion air system performance may differ from the test unit performance with regard to NO_x emission reductions and efficiency impact.

One must also be aware of the fact that the test unit was a crude oil heater. This type of furnace typically is one of the most flexible in a refinery in terms of tolerating changes in temperature and heat flux distributions. Other units such as reforming heaters and vacuum heaters often have process fluids of more than a single phase or at a higher temperature regime where the process fluid flow may be seriously affected by variations from a design heat flux distribution. These process limitations should be studied before attempting to apply the staged air modification to a process heater used for any such complex application.

4.1.2 Sizing the System

The size of the staged air blower, and the size of the piping (or ductwork) which delivers the air to the lances, and the size of the lances themselves must be determined based on the air flow rate required over the operating range of the particular heater. The number and arrangement of burners in the heater will determine the physical size and layout of the overall system.

In the field testing program it was found that four lances per burner at 90 degrees around the burner circumference provided the best NO_x reduction and flame characteristics. Additional lances would be more costly and would add an unreasonable amount of additional hardware to the unit thus hampering the operator's ability to properly inspect and adjust the burners, particularly in an emergency. With fewer lances in service, the NO_x reduction due to staged air was limited. Tests were conducted with half the lances in the firebox and the same staged air flow that had been injected with all of the lances in place (i.e., high velocity at the lance outlets). The amount of NO_x reduction dropped to almost half of its original value. Thus, the velocity of the staged air as well as the amount appear to be key parameters. It would be possible to reduce the number of lances per burner by increasing the diameter of each lance to maintain constant velocity. This design change could degrade performance but may be necessary for heaters with space limitations.

A. Staged Air Flow Rate--

The staged air system should be capable of providing roughly half of the total combustion air to be supplied to the heater assuming normal heater operation results in 20 percent excess air at the stack. At higher levels of excess air the staged air flow rate will be a greater percentage than half the total air and at lower levels of excess air the staged air flow rate will be less than half of the total air. In any case, the design point should be to provide approximately 50 percent of the theoretical amount of air required through the natural draft burners via the burner air registers and the remaining air through the staged air system.

For example, if the maximum thermal input to the heater is 16 MW (55 x 10 Btu/hr) and a gas fuel with a higher heating value of 37,000 kJ/m^3 (1000 Btu/scf) and a stoichiometric air/fuel ratio of 10/1 by volume is used, then the total amount of combustion air required (assuming 20 percent excess air is the normal operating condition) is calculated as:

$$\text{Volume flow rate of combustion air} = \frac{\text{Heat input}}{\text{HHV fuel}} \times \left(\frac{A}{F}\right)_{\text{stoic.}} \times \left(1 + \frac{\text{\% Excess air}}{100}\right)$$

For this example, the total combustion air flow rate would be 5.12 m^3/s (11,000 scfm). The stoichiometric air requirement is 4.33 m^3/s (9167 scfm).

The amount of air which would thus be handled by the staged air system would be equal to the total combustion air requirement minus 50 percent of the stoichiometric air or, in this case, nearly 60 percent of the total combustion air. Thus, the blower will have to be able to accommodate 2.99 m^3/s (6416 scfm) of air. Of course actual volume flow rate of air will depend on combustion air temperature and pressure at the heater site.

B. Lance Sizing--

The lance should be sized so as to provide air velocities at the lance tips of 61 to 91 m/s (200 to 300 ft/sec). The greater the velocity, the greater the penetration of the staged air jet and the greater the friction losses. A velocity in the middle of this range such as 76 m/s (250 ft/sec) is a good design point.

For a six-burner furnace 24 lances are required. Thus, for the staged air requirement calculated earlier the flow rate per lance would be 0.13 m^3/s (267 scfm). The lance diameter which will produce exit air velocities of 76 m/s may be calculated according to the equation:

$$d_{lance} = \sqrt{\frac{4}{\pi} \frac{Q_A}{v}}$$

where Q_A is the actual volume flow rate of air through each lance and v is the air velocity. The actual air flow rate through the lance may be estimated by using a typical lance air temperature measured on the prototype tests of 422 K (300°F) and using the relation:

$$Q_A = Q_{STD} \times \sqrt{\frac{T_A}{T_{STD}}}$$

The actual volume flow rate is thus calculated as 0.15 m^3/s (320 cfm). Using this value the ideal lance diameter may be determined to be 5.0 cm (1.97 in.). The range of lance diameters which may be considered is determined by the target velocity range discussed above. For this example the range of lance diameters would be 4.58 to 5.60 cm (1.80 to 2.20 in.). Thus, provided there is enough space around the burners for the lance penetrations into the firebox 2 in. pipe would suffice for the lances.

The lance material should be a high temperature stainless steel such as 316L grade. For high-intensity burners, lances may have to flame-sprayed with a ceramic coating to protect against oxidation. A temperature probe should be used to determine the possible lance skin temperature in the firebox prior to purchasing any lances in order to ascertain whether or not the materials under consideration will withstand the conditions. (The costs shown for the staged air system in Appendix A are for 316L stainless steel lances with no protective coating which worked well in the prototype system.) Temperatures of the lances were 450-500°F when air was flowing in the system.

C. Air Delivery Components--

The air delivery components of the staged air system may consist of either ductwork or standard schedule 40 carbon steel piping. A large manifold should be used to reduce friction losses. In general, the length of piping or ductwork from the manifold to each lance should be approximately constant for all lances so as to ensure roughly equal pressure drops for all lances. This will provide equal air distribution to all burners without the need for expensive valves or controls. (Such valves may be necessary in some instances where unequal air distribution is desired.)

It is recommended that the connection of the lance to the rest of the air delivery system be accomplished by threaded flanges. The flanged connection is durable and provides support for the lance. This type of connection provides a lower pressure drop than a flexible hose connection although it is not as easily adjustable when changes are desired in lance height or tip orientation.

Details of the air delivery system layout will vary with each application according to the needs and constraints of each plant. Two possible configurations are shown in Figure 4-2.

D. Blower and Motor Selection--

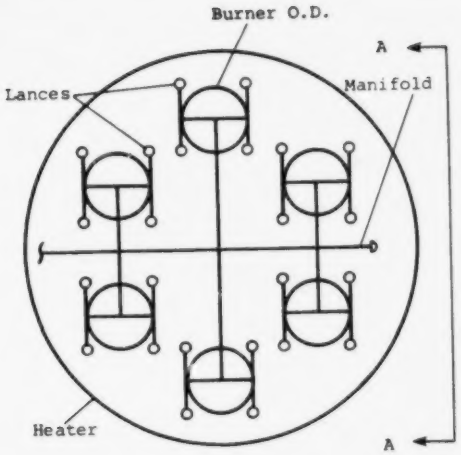
Since the blower is only subject to ambient air and since the furnace pressure is virtually ambient pressure the only problem is to properly select the blower and motor combination which will be able to produce the desired flow rate at a pressure sufficient to overcome the staged air delivery system pressure drop and provide the desired velocity head at the lance tips. The proper selection of a blower and motor depends upon a number of factors. The designer must have the fan performance curves and knowledge of the various fan and motor costs as well as the cost of electricity at his plant in order to make the selection. In addition, space limitations or noise constraints may dictate a certain wheel diameter or rotation speed. All of these items are addressed in great detail in sources such as Fan Engineering (Buffalo Forge Company, Buffalo, New York) and the detailed blower selection procedure will not be presented here.

For the sake of comparison a staged air system of the type given in the preceeding example would probably have a maximum pressure drop of about 5 kPa (20 in. H_2O) accounting for all of the fittings, valves, and exit losses in that system.

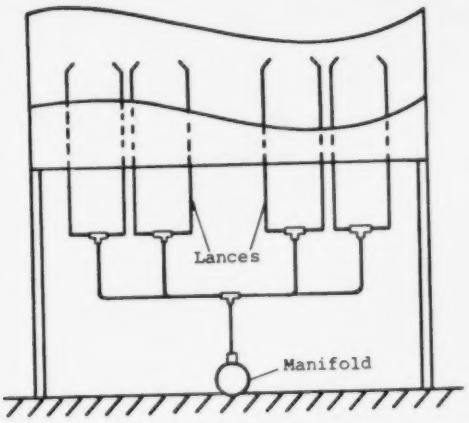
4.1.3 Instrumentation and Controls

A. Instrumentation--

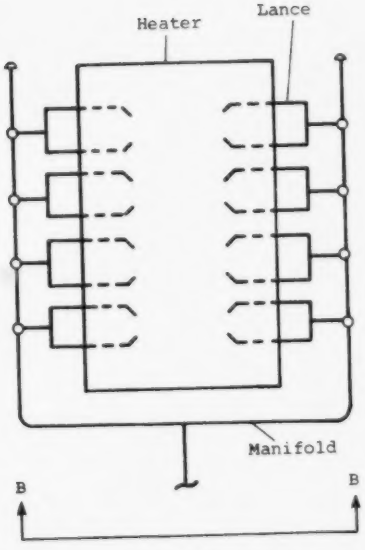
Since the staged air flow rate and lance tip velocity are important parameters in determining the amount of NO_x reduction achievable, it is desirable to have a total air flow measurement at the blower outlet as well as a measurement of the staged air temperature at the lance tips. A calibrated orifice or pitot-static tube and a fan discharge temperature gauge are required for the measurement of the total staged air flow. A thermocouple attached to the inside of a lance with the sensing junction suspended in the center of the lance at the base of the 45 deg. elbow will provide adequate lance air temperatures for the calculation of air injection velocities.



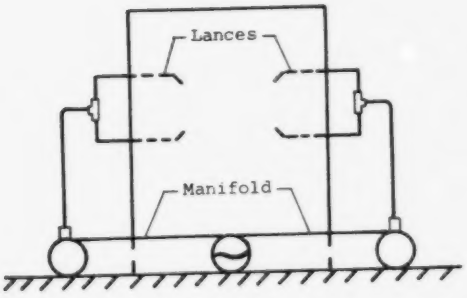
Vertical Cylindrical Heater
Plan View



Section A - A



Horizontal Rectangular Heater
Plan View



Section B - B

Figure 4-2. Suggested Staged Combustion Air System Schematics

In cases where the air flow to all lances is not equal, one may wish to know the air flow to certain individual lances. This may be accomplished simply by measuring the total air flow as described above and by measuring the blower outlet static pressure and the static pressure at the base of each lance for which flow information is desired. One may determine the velocity head at the base of the lance with this information and the knowledge of the friction losses in the the air delivery system and can use that data and the lance inside diameter to calculate the flow rate at the base of the lance. (The flow rate at the lance tip inside the firebox may be found by making the appropriate temperature correction using the lance air temperature measurement.)

In addition to measuring those parameters related directly to the staged air system it is highly desirable to obtain a continuous stack oxygen concentration. This is especially true when the heater is to be run at concentrations of 2 percent O_2 or less at the stack since fluctuations in feed rate or fuel composition to the heater (when burning refinery gas or oil) may cause significant departures from desired excess air levels. In the field tests of the prototype staged air device it was found that the full NO_x reduction potential of the system required that the stack O_2 be reduced from a baseline level of 4 percent to 2 percent. In long-term tests of the system it was found that continued operation of the heater at 2 percent stack O_2 necessitated the use of automatic O_2 control discussed below.

B. Controls--

As a minimum, the staged air system requires a manual blower inlet or outlet damper for control of the flow through the staged air system. Additional refinements to this simple system would include valves for individual burner air or for control of the air flow to clusters of burners, an automated staged air blower inlet or outlet damper, and either an automated stack damper coupled to an O_2 trim system or an automatic stack draft controller.

The oxygen-sensing automatic feedback/control system is the most direct way to control excess air since it measures a quantity (O_2) that is directly related to the amount of excess air present in the furnace. A microprocessor-based control system can have a preprogrammed O_2 versus load (feed

rate) curve covering the entire range of firing conditions just as is currently done on industrial and utility boilers.

The automatic draft controllers are simpler devices than O_2 trim systems since they have no feedback loop and do not require an oxygen analyzer. They control excess air indirectly, however, by controlling the furnace draft. While this type of system may require less maintenance, it may not control stack oxygen as well as the direct feedback/control system. Thus, fuel savings may be greater with the O_2 trim system in the long run.

It is important to realize that regardless of which type is used, some form of automatic control will be required to achieve optimum emissions and efficiency. In some cases the efficiency can pay for the additional cost of a controller (see Appendix A).

4.1.4 Recommended Safety Features

In order to protect against a potentially dangerous air deficiency to the heater in the event of a staged air blower failure a pressure switch at the blower discharge should be installed which will alert the operator to the sudden loss of blower discharge pressure. If an automated stack damper is installed the emergency signal from that switch should cause the damper to open fully and then proceed to close in small increments until the proper oxygen level is again reached.

An alarm may also be desired for lance skin temperature when lances are subject to very high furnace temperatures in order to protect against lance deformation due to overheating.

4.2 OPERATION AND MAINTENANCE

This section covers the initial startup and optimization testing of the staged combustion air system, the routine operation of the system, and recommended maintenance procedures.

4.2.1 Startup and Optimization

In order to accurately assess the effects of the staged air system on heater performance with respect to emissions and efficiency it is necessary to

first test the heater at baseline operating conditions without the staged air system in operation. The heater should be adjusted according to the procedures in Section 3 so that emissions and efficiency may be measured at "tuned" conditions over the load range capability of the unit.

Thus, a number of different stack O_2 conditions (preferably at least four different levels of O_2) should be tested at several different heater throughput rates. Emissions of NO_x, CO, and CO_2 (to serve as a check on the O_2 measurement) as well as stack gas temperature and the other operating variables mentioned in Section 3 should be recorded. Air registers should be adjusted at each condition as they would be in actual practice so as to give the best flame characteristics (i.e., stable flame with no impingement on tubes) and an acceptable draft profile.

At each process rate, the fuel flow should be held as constant as possible. If fuel composition tends to vary, samples should be taken at frequent intervals so that the firing rates may be calculated.

Once the heater has been characterized over its normal load range and at varying excess oxygen conditions the staged combustion air blower may be started. The air control damper should be opened slowly. The flames should be observed at all times when making changes in the staged air flows.

As the staged air flow increases the stack O_2 will also increase and the furnace draft will decrease. In order to maintain a constant stack O_2 and the desired negative pressure throughout the heater the stack damper and/or registers will have to be adjusted. In general, at low levels of staged air adjusting only the stack damper will suffice in providing the correct firing conditions. As the staged air system nears its air flow capacity, however, the tendency for stack O_2 to increase must be offset by closing down burner registers rather than closing the stack damper (starting with primary, then secondary, then tertiary registers) so that heater draft can be maintained.

Throughout this procedure one must monitor the flame for stability and impingement on tubes. It is also important to monitor process tube wall temperatures to ensure that the heat flux distribution is not being affected in a way which would disrupt the process or cause tube failures.

The staged air system should then be optimized to give the best overall performance. The parameters of importance are the following:

1. Stack O_2
2. Heater draft profile (air register settings)
3. Lance tip orientation
4. Staged air distribution
5. Lance insertion depth

To the extent possible each of these parameters should be varied with the other held constant during optimization testing. A proposed test matrix for this procedure is shown in Figure 4-3. It is assumed here that the staged air system will be operated at the maximum possible air flow rate which permits safe, reliable heater operation. If it is desired to determine system performance at lower air flow rates then the total staged air flow becomes a sixth test parameter.

In each test series the condition which results in the best overall heater performance (e.g., NO_x emissions, heater thermal efficiency, flame characteristics, etc.) should be determined. Since several different settings of each of the five test parameters is possible the test sequence shown in Figure 4-3 must be repeated several times in order to evaluate all possible combinations. (In practice one finds that the optimum lance tip orientation and the optimum staged air distribution are usually constant for all settings of the other test parameters so that the number of tests to perform is not unreasonable.)

During the parametric testing of this concept, it was found that a four-foot insertion depth was near optimum and little NO_x reduction was realized by increasing insertion depth. The lance tip orientation was also optimized and set with all tips oriented toward the heater centerline. This will vary according to heater/burner configuration, but once determined, can be fixed.

Parameter/ Test Series Number	Stack O_2	Heater Draft Profile	Lance Tip Orientation	Staged Air Distribution	Lance Insertion Depth
1	Vary	Fix	Fix	Fix	Fix
2	Fix	Vary	Fix	Fix	Fix
3	Fix	Fix	Vary	Fix	Fix
4	Fix	Fix	Fix	Vary	Fix
5	Fix	Fix	Fix	Fix	Vary
6	Repeat Test Series 1 through 4 as necessary				

Figure 4-3. Suggested Test Matrix for Staged Combustion Air System Optimization

4.2.2 Routine Operation

The normal operation of the staged air lance system requires very little attention. Aside from the routine heater operational checks for flame impingement, stack O_2, and heater draft mentioned in Section 3, the operator must check the condition of the lances periodically for scaling or large amounts of carbon deposition and for the proper skin temperature. The only other operational checks required are periodic inspections for leaks and proper air flow.

It is desirable both for the purpose of evaluating heater performance and in order to maintain the proper control of the heater to have a continuous display and record of stack oxygen in the control room. A continuous indication of furnace draft is also helpful when making changes in firing rate. Lance and process tube skin temperatures should be available to the operator on demand.

Stack O_2, furnace draft, lance and tube skin temperatures, and total staged air flow rate should be recorded by the operator periodically. They should be monitored closely whenever making adjustments to the heater.

4.2.3 Maintenance

Recommended maintenance items and intervals are listed below:

1. Staged air blower and motor - inspect periodically per normal plant standards for low temperature service.

2. Lances - inspect at least on a daily basis and whenever operating conditions change significantly; check for scaling and hot spots.

3. Oxygen analyzer - calibrate the analyzer daily; follow analyzer manufacturer's instructions for maintaining the sensing cell. Be certain to verify calibration gas concentrations as discussed in Section 3.

4. Automatic stack damper and blower damper controls (if so equipped) - inspect linkages and damper for proper response and freedom of movement periodically in accordance with plant standards.

5. Safety features and alarms - if a blower discharge pressure alarm is installed, inspect the sensing element and alarm periodically. If lances and/or process tube skin temperature alarms are installed inspect thermocouples monthly or as required.

SECTION 5.0

REFERENCES

1. Carter, W. A., et al., "Emission Reduction on Two Industrial Boilers with Major Combustion Modifications," EPA-600/7-78-099a, NTIS Order No. PB 283 109, June 1978.

2. Hunter, S. C., et al., "Application of Combustion Modifications to Industrial Combustion Equipment," EPA-600/7-79-015a, NTIS Order No. PB 294 214, January 1979.

3. Hunter, S. C., et al., "Application of Advanced Combustion Modifications to Industrial Process Equipment - Subscale Test Results," EPA-600/7-82-021, April 1982.

4. Tidona, R. J., et al., "Refinery Process Heater NO_x Reduction Using Staged Combustion Air Lances," EPA-600/7-83-022, March 1983.

5. Devitt T., et al., "Population and Characteristics of Industrial/ Commercial Boilers in the U.S.," EPA-600/7-79-178a, August 1979.

APPENDIX A

COST ANALYSIS OF STAGED COMBUSTION AIR APPLIED TO A NATURAL DRAFT PROCESS HEATER

A.1 LIMITATIONS OF THE ANALYSIS

The costs and NO_x reductions discussed in this section pertain to a permanent installation of staged combustion air lances retrofitted on a natural draft process heater firing either all gaseous fuel or a 50/50 mixture of residual oil and gas (by heat input rate). Costs for a system designed for a new installation would be substantially less.

Costs are given in November, 1981 dollars and represent KVB's best estimate of material and labor costs. They do not represent actual costs for any particular system.

NO_x reduction potentials are those obtained (a) during a long-term (30-day) test for gaseous fuel and (b) during short-term parametric tests for the combination oil/gas fuel.

A.2 INITIAL FIXED COSTS

The initial fixed costs of a permanent staged combustion air lance system are given in Table A-1. They apply to a system schematic essentially the same as that shown in Figure 4-1 except that lance connections are made using flanges rather than flexible hose. The piping for the system is schedule 40 carbon steel and the lances themselves are 316L stainless steel. The ball valves controlling air flow to each set of four lances have also been eliminated since the air distribution is nearly equal to each burner without the use of any flow control valves. Equal air distribution to each burner provided the best NO_x reduction capability during the parametric tests so it has been the guiding principle behind the permanent system design. In addition the blower size has been optimized. The permanent design uses a 2.08 m^3/s (4400 scfm) blower with a discharge pressure of 14 kPa (2 psi) and it is driven by a 44.8 kW (60 hp) electric motor.

TABLE A-1. INITIAL FIXED COSTS OF A PERMANENT STAGED COMBUSTION AIR SYSTEM FOR A NATURAL DRAFT PROCESS HEATER RATED AT 16.1 MW THERMAL INPUT

Item	Cost (November 1981 $)		
	Labor To Install	Material	Labor + Material
1. Civil and Structural (Foundations)	900	300	1,200
2. Blower, Motor, and Outlet Adapter	900	6,200	7,100
3. Pipe and Fittings, Lances, Installation of Couplings in Heater Floor	8,800	6,740	15,540
4. Instrumentation	50	250	300
5. Electrical (including starter for motor)	3,600	4,470	8,070
6. Engineering	8,000	300	8,300
7. Construction	4,000	2,200	6,200
8. Indirect (including taxes, contingency, etc.)	--	3,000	3,000
TOTALS	$26,250	$23,460	$49,710

In order to realize the full NO_x reduction potential of the staged combustion air (SCA) system it is necessary to reduce the stack oxygen content from a normal operating level (4 percent O_2) to an optimum low level (2 percent O_2) by installation of an automatic O_2 controller.

From Ref. A-1 the initial costs for the staged air system may be conservatively estimated to scale with heater size (heat input rate) to the 2/3 power.

A.3 ANNUAL OPERATING AND MAINTENANCE COSTS

For the application of staged combustion air only, one must consider the annual blower electricity costs, the annual maintenance costs on the blower and staged air lances, and the annual fuel savings resulting from the efficiency increases due to the addition of the SCA system.

In order to reduce stack oxygen from the normal operating level (4 percent O_2) to an optimum low level (2 percent O_2) one must consider maintenance costs of an automatic air control system as well as the fuel savings which result from the lowered stack losses. The costs are expected to be minimal - only about $200/year.

The costs of operating the staged air blower in the permanent design system may be determined assuming that the blower motor will operate at design capacity (i.e., 45 kW) and assuming a use factor for the heater of 0.70 (to account for normal down time on the heater as well as normal operating heat input rate relative to design capacity). We will also assume an electrical-to-mechanical conversion efficiency in the motor of 85 percent. The calculation proceeds as follows using the test plant's electrical energy cost of 5.5¢/kW-h:

Annual Blower Electrical Energy cost

$$= 45 \text{ kW} \times 0.70 \times \frac{1}{0.85} \times 8760 \frac{\text{h}}{\text{y}} \times \frac{\$0.055}{\text{kW-h}}$$

$$= \$17,855$$

This cost will change slightly with changes in operating conditions such as excess air level, however the magnitude of the change will be small compared to the total cost.

In the absence of more detailed information the staged air system annual maintenance costs are assumed to be 3 percent of the initial fixed costs. This amounts to $1500 per year. This is typical for refineries (Ref. A-2).

The fuel savings which result from the application of staged combustion air at 4 percent stack O_2, the savings due to the use of lowered excess air only, and due to the use of SCA and LEA combined were shown in Table A-1. These values may be converted into cost savings using the plant's gas fuel cost of $\$3.44/10^6$ Btu or $0.0119/kW-h and the heater use factor of 0.70. These values are shown in Table A-2. The values are calculated from the decreases in fuel consumption which occurred firing gas fuel only since those are more conservative than the fuel savings associated with the firing of No. 6 oil and gas. The annual unmodified fuel consumption is thus determined:

$$16{,}115 \text{ kW} \times 8760 \frac{\text{h}}{\text{y}} \times 0.70 = 98.82 \cdot 10^6 \text{ kW-h/y}$$

The cost of this fuel is thus:

$$98.82 \cdot 10^6 \frac{\text{kW-h}}{\text{y}} \times \frac{\$0.0119}{\text{kW-h}} = \$1{,}176{,}000/\text{y}$$

TABLE A-2. FUEL SAVINGS (NOV., 1981 $) DUE TO COMBUSTION MODIFICATIONS TO A NATURAL DRAFT PROCESS HEATER RATED AT 16.1 MW THERMAL INPUT

Modification	Percent Decrease in Fuel Consumption	Savings ($)
1. Staged Combustion Air (SCA) at 4% O_2	0.2	2,320
2. Lowered Excess Air (LEA)	2.8	32,485
3. SCA + LEA	3.1	35,965

The annual fuel savings of any of the above modifications will be roughly proportional to heater size (in heat input). The blower electrical cost associated with modifications 1 and 3 will also rise linearly with unit heat input rate since the heat in is proportional to the total volume of combustion air with small variations due to different fuel compositions. Since a constant burner stoichiometric ratio is desired for any unit, the volume of staged air flow, Q, is a fixed percentage of the total flow for any size heater (in this analysis the staged air flow represents about 40 percent of the total combustion air flow at 4 percent stack O_2 and about 50 percent of the total air flow at 2 percent stack O_2). Also, the power required to drive the blower is directly proportional to the volumetric flow rate of air, Q, through the blower. The annual maintenance costs for both staged air and the automatic draft controller are expected to increase with heater size to the 2/3 power, since they are a fixed percentage of the initial costs.

To summarize the preceding relationships:

1) Initial Fixed Costs (IFC) $\propto MW^{2/3}$,

2) Annual Maintenance Costs = 0.03 x IFC, thus

3) Annual Maintenance Cost $\propto MW^{2/3}$,

4) Annual Fuel Savings $\propto MW^{1}$, and

5) Annual Blower Electricity Costs $\propto MW^{1}$.

For a natural draft heater rated at 16.1 MW thermal input the annual costs of combustion modifications are given in Table A-3. Values in parenthesis represent a savings.

A.4 TOTAL ANNUALIZED COSTS

The assumptions made in determining the total annualized costs for a 16.1 MW_{th} natural draft process heater are given in Table A-4.

The total annualized costs are calculated by adding the annual costs including taxes and insurance to the annualized capital costs. These costs are presented in Table A-5 for the following modifications applied to a

TABLE A-3. ANNUAL OPERATING COSTS (NOV., 1981 $)
OF COMBUSTION MODIFICATIONS TO A NATURAL DRAFT PROCESS HEATER
RATED AT 16.1 MW THERMAL INPUT

Item	SCA* Only (4% O_2)	LEA* Only (4% O_2 → 2% O_2)	SCA + LEA
Blower Electricity	17,855	0	17,855
Maintenance	1,500	200	1,500
(Fuel Savings)	(2,320)	(32,485)	(35,965)
Totals, cost (savings)	17,035	(32,285)	(16,610)

*SCA = Staged Combustion Air

LEA = Lowered Excess Air

TABLE A-4. ASSUMPTIONS MADE IN DETERMINING TOTAL ANNUALIZED COSTS

1. State and Federal Property Taxes = 11% of Initial Capital Cost
2. Insurance Charges = 0.5% of Initial Capital Cost
3. Straight-Line Depreciation Over 12 Years
4. State and Federal Income Taxes = 50%
5. Investment Tax Credit (First Year Only) = 10%
6. 100% Equity Financing (Debt/Equity = 0)
7. 15% Rate of Return
8. Capital Recovery Factor = 0.2773

TABLE A-5. TOTAL ANNUALIZED COSTS OF COMBUSTION MODIFICATIONS ON A 16.1 MW_{th} NATURAL DRAFT PROCESS HEATER

Item	Costs (November 1981 $)		
	SCA* @ 4% O_2	LEA* Only	SCA + LEA
Annual Operating Cost (Savings)	17,035	(32,285)	(16,610)
State and Federal Taxes (11% of IFC)	5,468	4,400	9,868
Insurance (0.5% of IFC)	249	200	449
Subtotal, costs (savings)	22,752	(27,685)	(6,293)
Initial Fixed Costs	49,710	40,000	89,710
Annual Capital Charge	13,785	11,092	24,877
Total Annualized Costs (savings)	36,537	(16,593)	18,585

*SCA = Staged Combustion Air

LEA = Lowered Excess Air

16.1 MW_{th} process heater: SCA at 4 percent O_2, LEA only, and the combination of SCA plus LEA.

To a first approximation the total annualized cost of SCA applied at 4 percent O_2 may be related to the heat input rate of the heater by using the cost scaling factors presented in Section A.3. Calculations of total annualized costs (savings) for staged air applied at 4 percent O_2 , lowered excess air only, and staged air plus lowered excess air are shown for heater sizes of 29.3 MW (100 x 10^6 Btu/h) and 147 MW (500 x 10^6 Btu/h) in Tables A-6 and A-7.

The costs for SCA at 4 percent O_2 are plotted versus heat input rate in Figure A-1. From that log-log plot one may determine an approximate power law for the total annualized costs. The slope of the curve shown in Figure A-1, is approximately 0.86. Thus,

$$\frac{\text{Cost at Size 1}}{\text{Cost at Size 2}} = \left(\frac{MW_1}{MW_2}\right)^{0.86}$$

This is valid for heat input rates between 3 MW and 147 MW.

Of course, one observes from Tables A-5, A-6, and A-7 that lowered excess air gives increasing savings as heater size increases. It will clearly be advantageous to apply this modification from the standpoint of economics alone.

For the combination of staged air and lowered excess air, however, an interesting situation develops. The total annualized costs rise for heaters less than 29.3 MW thermal input but than fall off for still larger heaters until at the 147 MW_{th} size, a savings is actually realized. This indicates that for very large heaters, plants can actually consider the combination modification a capital investment rather than strictly a capital expense item as would be the case for the staged air modification without the addition of lowered excess air. This is true regardless of NO_x reduction capability of the modifications.

TABLE A-6. TOTAL ANNUALIZED COSTS OF COMBUSTION MODIFICATIONS ON A 29.3 MW_{th} NATURAL DRAFT PROCESS HEATER

Item	Costs (November 1981 $)		
	SCA* @ 4% O_2	LEA* Only	SCA + LEA
Annual Operating Cost (Savings)	30,508	(58,821)	(30,722)
State and Federal Taxes (11% of IFC)	8,151	6,559	14,709
Insurance (0.5% of IFC)	370	298	669
Subtotal, costs (savings)	39,029	(51,964)	(15,344)
Initial Fixed Costs	74,098	59,624	133,722
Annual Capital Charge	20,547	16,534	37,081
Total Annualized Costs (savings)	59,576	(35,430)	21,737

*SCA = Staged Combustion Air

LEA = Lowered Excess Air

TABLE A-7. TOTAL ANNUALIZED COSTS OF COMBUSTION MODIFICATIONS ON A 147 MW_{th} NATURAL DRAFT PROCESS HEATER

Item	Costs (November 1981 $)		
	SCA* @ 4% O_2	LEA* Only	SCA + LEA
Annual Operating Cost (Savings)	159,442	(295,728)	(158,799)
State and Federal Taxes (11% of IFC)	23,887	19,221	43,108
Insurance (0.5% of IFC)	1,086	874	1,959
Subtotal, costs (savings)	184,415	(275,633)	(113,732)
Initial Fixed Costs	217,156	174,738	391,894
Annual Capital Charge	60,217	48,455	108,672
Total Annualized Costs (savings)	244,632	(227,178)	(5,060)

*SCA = Staged Combustion Air

LEA = Lowered Excess Air

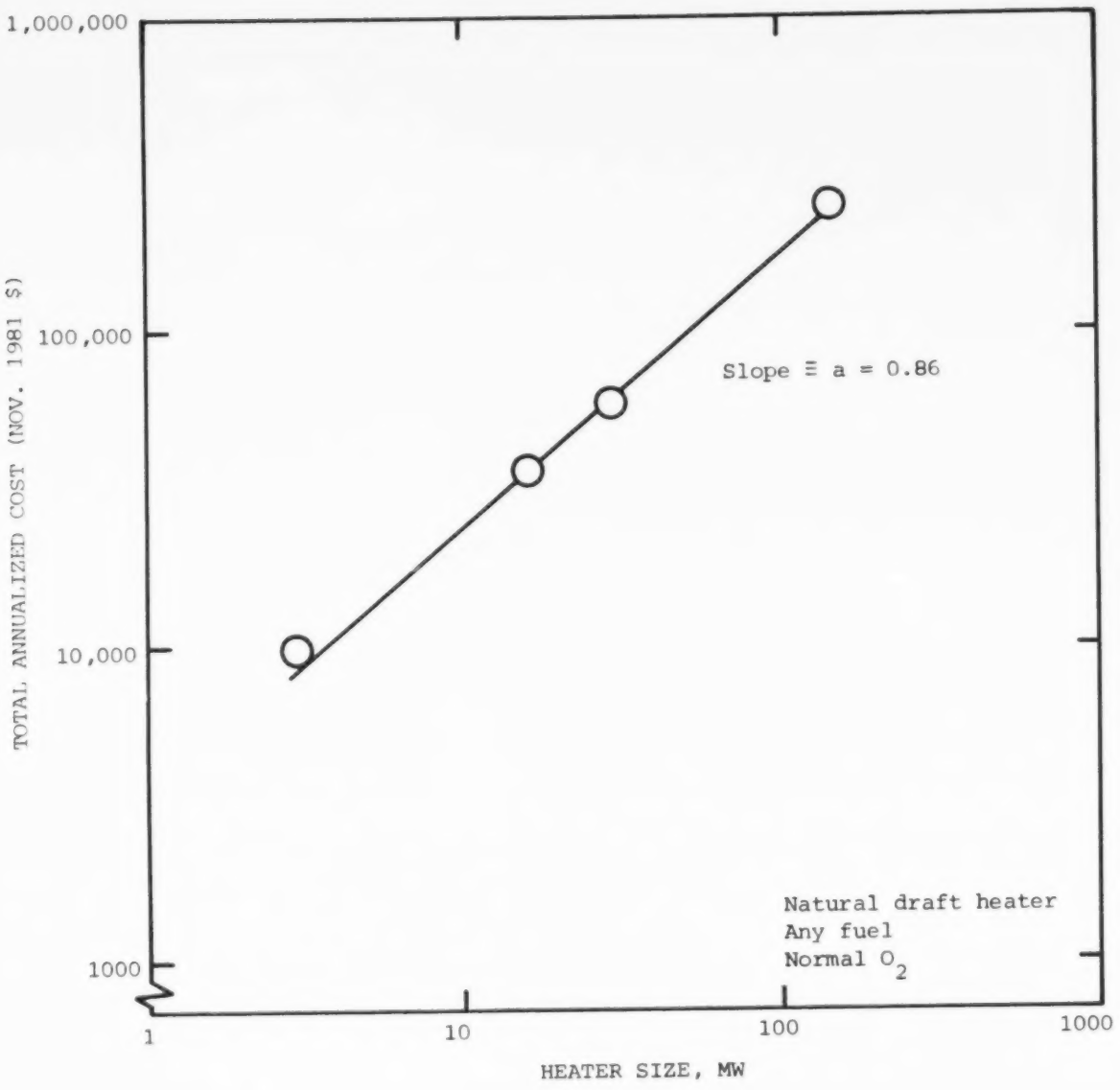


Figure A-1. Total annualized costs as a function of design heat input capacity for natural draft process heaters with staged combustion air at normal stack oxygen.

A.5 COST/EFFECTIVENESS RATIO

The cost/effectiveness ratio of staged combustion air applied at 4 percent O_2 and of the combined SCA/LEA modification is determined here. The cost effectiveness, CE, is defined as the total annualized costs divided by the annual NO_x reduction potential to give a dollar amount per metric ton of NO_x removed by the modification.*

The annual NO_x reduction potential is given for three heater sizes in Table A-8.

These calculations assume a NO_x reduction capability of 39 ng/J for the staged combustion air system and apply to both gaseous fuel and to the 50/50 mixture of gas and No. 6 oil fuel. This number is the difference between the unmodified NO_x emission and the emission rate with SCA applied at 4 percent O_2. By once again assuming a use factor of 0.70 for the heater the calculation of NO_x emission reduction potential at the 16.1 MW size proceeds as follows:

NO_x Reduction Potential

$$= 16.1 \times 10^6 \frac{J}{s} \times 0.70 \times 8760 \frac{h}{y} \times 3600 \frac{s}{h} \times 39 \times 10^{-15} \frac{Mg}{J}$$

$$= 13.86 \frac{MG}{Y}$$

It is expected that the change in emission factor due to combustion modification will hold approximately for all heater sizes so that the NO_x reduction potential will scale linearly with heat input rate.

For the combination of staged air and lowered excess air the NO_x reduction potential is assumed to be 48 ng/J which was the value for gas firing. This is conservative relative to the value for gas/oil firing which was 60 ng/J.

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*A lower value of cost/effectiveness ratio indicates a more desirable control method.

TABLE A-8. ANNUAL NO_x REDUCTION POTENTIAL (Mg) OF COMBUSTION MODIFICATIONS AT THREE HEATER SIZES

Modification*	Heater Size		
	16.1 MW	29.3 MW	147 MW
SCA at 4% O_2	13.86	25.22	126.5
SCA + LEA	17.06	31.05	155.8
LEA only (gas fuel)	2.84	5.17	47.2
LEA only (gas + No. 6 oil)	11.37	20.69	103.8

*SCA = Staged Combustion Air

LEA = Lowered Excess Air

For lowered excess air alone the NO_x reduction potential differed for the gaseous fuel and for the combination fuel. The reduction in NO_x emission factor firing gas was only 8 ng/J whereas it was 32 ng/J firing oil and gas. The two results are shown separately in Table A-8.

The cost/effectiveness ratio of combustion modifications applied to three heater sizes is shown in Table A-9. The values for LEA and for SCA plus LEA modification on the largest heater are negative indicating a savings in combination with a NO_x reduction. This is a desirable situation, however, one must realize that a modification which saves money yet produces only a small NO_x reduction will have a large negative cost/effectiveness ratio. This may not be the most desirable modification if the level of NO_x reduction is lower than is necessary to achieve compliance with regulations or to offset future emissions from plant expansions.

The cost and cost/effectiveness ratio of staged combustion is compared with that of other commercially available modifications in Table A-10 for a 29.3 MW (100 x 10^6 Btu/h) natural draft process heater. The values for low-NO_x burners and for selective non-catalytic reductions are developed from

TABLE A-9. COST/EFFECTIVENESS RATIO ($/Mg) OF COMBUSTION MODIFICATIONS APPLIED TO THREE NATURAL DRAFT PROCESS HEATER SIZES

Modification	Heater Size		
	16.1 MW	29.3 MW	147 MW
Staged Combustion Air at 4% O_2	2636	2362	1934
Staged Combustion Air + Lowered Excess Air	1089	700	(40)*
Lowered Excess Air Firing Gas	(5843)*	(6853)*	(4813)*
Lowered Excess Air Firing Oil and Gas	(1459)*	(1712)*	(2189)*

*Savings

Ref. A-3. The values for cost/effectiveness ratio from Ref. A-3 have been adjusted to include state and federal taxes and a capital annualization factor of 0.2773. Fuel penalties were already included where efficiencies were reduced by modifications discussed in Ref. A-3, however, no credit was taken in Ref. A-3 for fuel savings where efficiencies increased due to a modification. Thus, the usual fuel savings due to installation of low-NO_x burners (since they often operate at lower excess air than standard burners) is not accounted for in Table A-10. Note also that the column "Annual Operating Costs (Savings)" does not include taxes or insurance, however these items are accounted for in the cost effectiveness column.

From Table A-10, one observes that for a natual draft heater firing gas fuel both the percent NO_x reduction and the cost/effectiveness ratio of staged combustion compare favorably to other commercially available combustion modification techniques. Lowered excess air is certainly the most desirable modification from a financial standpoint, however it offers the least NO_x reduction capability. For oil-fired heaters, however, the NO_x reduction capability of LEA may approach both low-NO_x burners and staged combustion lances (applied at normal O_2).

TABLE A-10. COST OF VARIOUS CONTROL TECHNOLOGIES APPLIED TO A 29.3 MW NATURAL DRAFT PROCESS HEATER

Type of Control	Approximate Percent NO_x Reduction	Installed Capital Cost $/MW	Annual Operating Costs (Savings) $/Year	Average Cost/ Effectiveness Ratio $/Mg	$/lb
Lowered Excess Air (gas fuel)	15	2,035	(58,821)	(6,853)	(3.11)
Low-NO_x Burners	35	2,915	--	2,599	1.18
Selective Noncatalytic Reduction	50	4,266	46,089	5,176	2.35
Staged Combustion Air, Normal O_2 (gas fuel)	60	2,529	30,508	2,362	1.07
Staged Combustion Air, Low O_2 (gas fuel)	71	4,563	(30,722)	700	0.32

The costs of a staged combustion air system on a natural draft heater may be looked at in another way. The additional cost of NO_x control per barrel of oil produced may be calculated for the present test heater as follows:

$$\frac{\Delta \text{Cost}}{\text{Unit of Throughput}} = \frac{\text{Total annualized cost of } NO_x \text{ control}}{\text{Annual Crude Throughput}}$$

For the present heater this works out to 5.5¢/m^3 (0.9¢/bbl) for SCA applied at 4 percent O_2. Even if this modification were applied at several steps in the oil production process, the maximum increase in oil production costs may be seen to be minimal. Compared to the initial cost of the crude, the total NO_x control costs would probably be less than 0.2 percent.

A.6 REFERENCES

A-1 Hunter, S. C. et al., "Application of Advanced Combustion Modifications to Industrial Process Equipment - Subscale Test Results," EPA-600/7-82-021, April 1982.

A-2 Cherry, S. S. and Hunter, S. C., "Cost and Cost Effectiveness of NO_x Control in Petroleum Industry Operations," American Petroleum Institute Publication No. 4331, October 1980.

A-3 South Coast Air Quality Management District and Stationary Source Control Division, Air Resources Board, Joint Staff Report, SS-81-016, "Public Meeting to Consider a Suggested Control Measure for the Control of Emissions of Oxides of Nitrogen from Boilers and Process Heaters in Refineries," October 1981.

APPENDIX B

CONVERSION FACTORS
SI units to Metric or English units

To Obtain	From	Multiply By
g/Mcal	ng/J	0.004186
10^6 Btu	GJ	0.948
Btu	gm cal	3.9685×10^{-3}
lb/10^6 Btu	ng/J	0.00233
ft	m	3.281
in.	cm	0.3937
ft^2	m^2	10.764
ft^3	m^3	35.314
lb	kg	2.205
Fahrenheit	Celsius	$t_F = 9/5(t_c) + 32$
Fahrenheit	Kelvin	$t_F = 1.8t_K - 460$
psig	Pa	$P_{psig} = (P_{pa})(1.450 \times 10^{-4}) - 14.7$
psia	Pa	$P_{psia} = (P_{pa})(1.450 \times 10^{-4})$
iwg (39.2°F)	Pa	$P_{iwg} = (P_{pa})(4.014 \times 10^{-3})$
10^6 Btu/hr	MW	3.413
GJ/hr	MW	3.60

To obtain ppm at 3% O_2 of	Multiply* Concentration in ng/J by
Natural Gas Fuel	
CO	3.23
HC	5.65
NO or NO_x	1.96
SO_2 or SO_x	1.41
Oil Fuel	
CO	2.93
HC	5.13
NO or NO_x	1.78
SO_2 or SO_x	1.28
Coal Fuel	
CO	2.69
HC	4.69
NO or NO_x	1.64
SO_2 or SO_x	1.18

*These conversions depend on fuel composition.
The values given are for typical fuels.

English and Metric Units to SI Units

To Obtain	From	Multiply By
ng/J	$lb/10^6$ Btu	430
ng/J	g/Mcal	239
GJ	10^6 Btu	1.055
m	ft	0.3048
cm	in.	2.54
m^2	ft^2	0.0929
m^3	ft^3	0.02832
kg	lb	0.4536
Celsius	Fahrenheit	$t_c = 5/9\ (t_F - 32)$
Kelvin	Fahrenheit	$t_K = 5/9\ (t_F - 32) + 273$
Pa	psig	$P_{pa} = (P_{psig} + 14.7)(6.895 \times 10^3)$
Pa	psia	$P_{pa} = (P_{psia})(6.895 \times 10^3)$
Pa	iwg (39.2°F)	$P_{pa} = (P_{iwg})(249.1)$
MW	10^6 Btu/hr	0.293
MW	GJ/hr	0.278

To obtain ng/J of	Multiply* Concentration in ppm @ 3% O_2 by
Natural Gas Fuel	
CO	0.310
HC	0.177
NO or NO_x (as NO_2)	0.510
SO_2 or SO_x	0.709
Oil Fuel	
CO	0.341
HC	0.195
NO or NO_x (as NO_2)	0.561
SO_2 or SO_x	0.780
Coal Fuel	
CO	0.372
HC	0.213
NO or NO_x (as NO_2)	0.611
SO_2 or SO_x	0.850

*These conversions depend on fuel composition.
The values given are for typical fuels.

APPENDIX C

EMISSION CORRECTION FACTORS FOR FLUE GAS MOISTURE CONTENT AND EXCESS AIR

Pollutant emissions such as NO, NO_2, SO_2, SO_3, and CO as measured by various means must be reported on some standard basis. Often, a species concentration is measured as a fraction of the total volume of flue gas. The resulting measurement, either in ppmV (parts per million by volume) or percent, is said to be on a wet basis and uncorrected for any dilution of the flue gases by excess air. In order to present all emissions on a comparable basis the practice which has become standard for boiler emissions work has been adopted also for process heaters. Thus, volume concentrations of flue gas constituents are reported on a dry basis and corrected to 3 percent O_2 (that is, the concentrations that would be observed if all of the moisture were removed from the flue gas and if enough air were removed from the flue gas so that only 3 percent of the remaining flue gas consisted of oxygen).

The concentration of a species, corrected to a dry basis, is therefore higher than the concentration reported on a wet basis. The subsequent correction to 3 percent O_2 results in a still higher number for the final corrected concentration when the stack gas O_2 content is greater than 3 percent and a lower number when the stack gas O_2 content is less than 3 percent.

The formula for correcting emissions to a dry basis when measured on a wet basis is the following:

$$(C_i)_{dry} = \frac{(C_i)_{wet}}{1 - \frac{\% H_2O}{100}}$$

where C_i is the concentration of species i in ppmV or percent by volume and % H_2O is the percent moisture in the stack gas. Once a dry emission measurement is obtained it should be corrected to 3 percent O_2 as follows:

$$(C_i)_{\substack{dry,\\ 3\%\ O_2}} = \frac{17.95}{20.95 - (\%\ O_2)_{dry}} \times (C_i)_{dry} \text{ @ measured } O_2 \text{ concentration}$$

where $(\%\ O_2)_{dry}$ is the concentration of oxygen measured on a dry basis in the stack gas.